ASSOCIATIONS BETWEEN GAIT AND ISOMETRIC LOWER LIMB STRENGTH FOLLOWING STROKE

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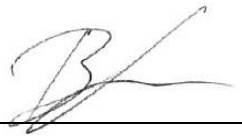

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ABSTRACT

Stroke is a leading cause of disability worldwide. The most commonly stated goal following stroke is to regain the ability to walk independently, resulting in a large amount of rehabilitation time focussed on gait retraining. Identification of key variables that relate to and affect gait function is important in order to understand the factors associated with impaired gait and to guide future intervention strategies. Reduced muscle strength has been proposed as a key contributor to physical limitations after stroke and is commonly assessed in clinical and research settings. The aim of this thesis was to examine the associations between lower limb isometric strength and gait following stroke.

A systematic literature review was conducted for Study One in order to collate the results of previous research which reported on the correlations between muscle strength and gait velocity following stroke. The review identified 21 articles that had examined this association with varied results. The majority of the identified studies had a small sample size ($n \leq 30$) and received low scores for methodological quality. The studies with a larger sample size and methodological quality revealed a trend which suggested the strength of the ankle dorsiflexors provides the strongest bivariate association with gait velocity. Due to the limitations of the included studies, further research is needed.

Another important consideration of muscle function is not only the peak amount of force a muscle group can produce (muscle strength) but how quickly force can be produced (muscle power). The second study of this thesis examined the psychometric properties of a clinically accessible device, hand-held dynamometry, for assessment of isometric muscle strength and power. The results from Study Two showed that hand-held dynamometry demonstrated acceptable reliability across eight lower limb muscle groups for the assessment of isometric strength and power in a healthy and unimpaired cohort. Concurrent validity of hand-held

dynamometry also demonstrated acceptable results for the majority of lower limb muscle groups when compared against a laboratory-based fixed dynamometer. The muscle groups of the ankle were found to have lower than expected validity, however this may be due to the ankle attachment used on the fixed dynamometer, which demonstrated larger measurement error. Nevertheless, hand-held dynamometry has shown promising results for assessment of strength and power for the muscles of the lower limb in a sample of adults without impairments.

To expand on the results of the systematic review (Study One), Study Three provided a detailed analysis of the relationships between isometric strength and gait velocity following stroke, as well as examining a previously underutilised outcome measure in the stroke population, isometric muscle power. Study Three was undertaken to examine if isometric power provided additional value in the relationship with gait velocity over muscle strength and to determine which muscle group of the lower limb demonstrates the strongest relationship with gait velocity. Results revealed isometric strength provided significant additional value in the relationship with gait velocity over isometric power. Comparison of seven lower limb muscle groups revealed the strength of the ankle plantarflexors and hip flexors to explain the most variance in gait velocity.

The final study of this thesis (Study Four) examined the relationship between isometric measures of strength and power, assessed with hand-held dynamometry, and joint power generation during gait following stroke. Ankle plantarflexor strength and power showed a significant relationship with peak ankle joint power generation during gait. Similar to Study Three, comparison between strength and power revealed ankle plantarflexor strength had a stronger relationship over ankle plantarflexor power.

The program of research presented in this thesis found hand-held dynamometry provided psychometrically-sound measures of isometric strength and power. The relationship between hand-held dynamometry derived measures of strength and power with gait function revealed isometric strength provided additional value over isometric power. The strength of the ankle plantarflexors demonstrated a strong relationship with gait velocity and ankle power generation during gait. Future research may examine the ankle plantarflexors further to see if improved plantarflexor strength results in improved gait function following stroke. This thesis provides a substantial contribution to the knowledge in this field and may assist clinical decision making when considering gait function post-stroke as well as guiding future research in the design of intervention strategies aimed at improving gait.

LIST OF ABBREVIATIONS

1RM	One-repetition maximum
3DGA	Three-dimensional gait analysis
APG	Ankle power generation
HHD	Hand-held dynamometry
HHDs	Hand-held dynamometers
ICCs	Intraclass correlation coefficients
MDC	Minimal detectable change
MeSH	Medical subject headings
MVC	Maximal voluntary contraction
RFD	Rate of force development
RTD	Rate of torque development
SEM	Standard error of measurement

CHAPTER ONE: INTRODUCTION

1.1 Background

Stroke is a leading cause of disability worldwide (Adamson, Beswick, & Ebrahim, 2004; Feigin et al., 2014) that can result in a range of physical limitations or impairments. The restoration of walking function has long been accepted as a key goal following stroke, with a large amount of rehabilitation time focused on gait retraining (Latham et al., 2005; Tole, Williams, Clark, & Holland, 2014). Gait velocity is an important clinical measure that is indicative of overall gait performance in stroke (Teixeira-Salmela, Nadeau, McBride, & Olney, 2001) and has been shown to be a discriminative clinical measure that can be predictive of length of hospital stay, functional outcome and community ambulation (Lord, McPherson, McNaughton, Rochester, & Weatherall, 2004; Perry, Garrett, Gronley, & Mulroy, 1995; Salbach et al., 2001). The joint power generated throughout the gait cycle (a dynamic measure that assists with forward propulsion during walking) is another important measure of gait function following stroke (Olney, Griffin, Monga, & McBride, 1991). Deficits in joint power generation during gait can impede the ability to achieve healthy gait speeds, with studies showing a strong relationship between joint power generation and gait velocity following stroke (Kim & Eng, 2004; Olney, Griffin, & McBride, 1994; Olney et al., 1991). The identification of key variables that relate to and affect measures of gait is important to build a better clinical understanding of the factors associated with impaired gait and therefore guide future intervention strategies.

Reduced muscle strength has been proposed as a key contributor to physical limitations after stroke (Ada, Dorsch, & Canning, 2006; Bohannon, 1989b; Canning, Ada, Adams, & O'Dwyer, 2004). While there are many methods used to measure muscle strength, this thesis

will focus on isometric measures of strength due to the ability to test single muscle groups quickly and easily in a clinical setting. There is a plethora of research examining how isometric muscle strength relates to gait velocity, with differences in results depending on a range of factors including the sample size involved and the muscle groups assessed (Bohannon, 1986a, 1989b; Dorsch, Ada, Canning, Al-Zharani, & Dean, 2012; Ng & Hui-Chan, 2012). Many of the previous studies examining the associations between isometric strength and gait velocity have only examined the strength of the knee extensors (Bohannon & Andrews, 1990; Liu-Ambrose, Pang, & Eng, 2007; Nakamura, Hosokawa, & Tsuji, 1985). It is possible that other muscle groups, especially those that act to produce forward progression of the body when walking, may provide a stronger link with gait parameters following stroke.

Previous research has also examined how measures of isometric muscle strength are associated with joint power generation during gait, albeit in other neurological populations such as cerebral palsy and traumatic brain injury (Dallmeijer, Baker, Dodd, & Taylor, 2011; Kahn & Williams, 2015). Moderate correlations have been found between isometric muscle strength and joint power generation in these populations (Dallmeijer et al., 2011; Kahn & Williams, 2015), however this relationship has not previously been examined in the stroke population.

Muscle power is another important component of physical function, with evidence indicating that measures of muscle power are more strongly associated with self-reported function, incidence of falls and physical performance than muscle strength in the elderly (Bean et al., 2002; Foldvari et al., 2000; Skelton, Kennedy, & Rutherford, 2002). Previous research in the area of muscle power in stroke has been limited and has used expensive and cumbersome equipment, potentially precluding these methods in the clinical setting. One

previous study of people with stroke has shown that measures of muscle power provided a stronger relationship with gait velocity compared with muscle strength (Pohl et al., 2002), highlighting the potential importance of muscle power in stroke rehabilitation. Measures of muscle power may also provide additional information to better understand the relationship with joint power generation during gait over measures of muscle strength.

1.2 Research Questions

The main research questions addressed in this program of research are:

1. What are the previously reported associations between lower limb isometric muscle strength and gait velocity following stroke? (Study One)
2. What are the psychometric properties of hand-held dynamometers (HHDs) for the assessment of isometric muscle strength and power in both the unimpaired and stroke populations? (Study Two and Three)
3. The strength and power of which muscle group has the strongest relationship with gait velocity after stroke? (Study Three)
4. Which measure of isometric muscle function (strength or power), when measured using hand-held dynamometry (HHD), has the strongest relationship with gait velocity following stroke? (Study Three)
5. What is the relationship of strength and power, when measured using HHD, with joint power generation during gait after stroke? (Study Four)

1.3 Aims

The main aims of this thesis are to:

1. Systematically review and appraise the literature investigating the associations between isometric muscle strength and gait velocity following stroke (Study One);
2. Examine the psychometric properties of HHDs for the assessment of isometric muscle strength and power in unimpaired and stroke cohorts (Study Two and Three);
3. Investigate the strength and power of the lower limb muscle groups to determine which muscles have the strongest relationship with gait velocity after stroke (Study Three);
4. Compare the relationships between isometric strength and power with gait velocity following stroke (Study Three);
5. Investigate the relationship of strength and power, measured with HHD, with joint power generation during gait following stroke (Study Four).

1.4 Synopsis

The overall structure of this thesis is summarised by the concept map provided in Figure 1.1. This concept map outlines the study structure of this program of research and the interactions between each study. An extended methodology chapter was not included in this thesis, with a detailed description and discussion of the methods used in this thesis contained within each study. Following the concept map, each study is summarised with a brief description of the specific rationale, aims and research design used.

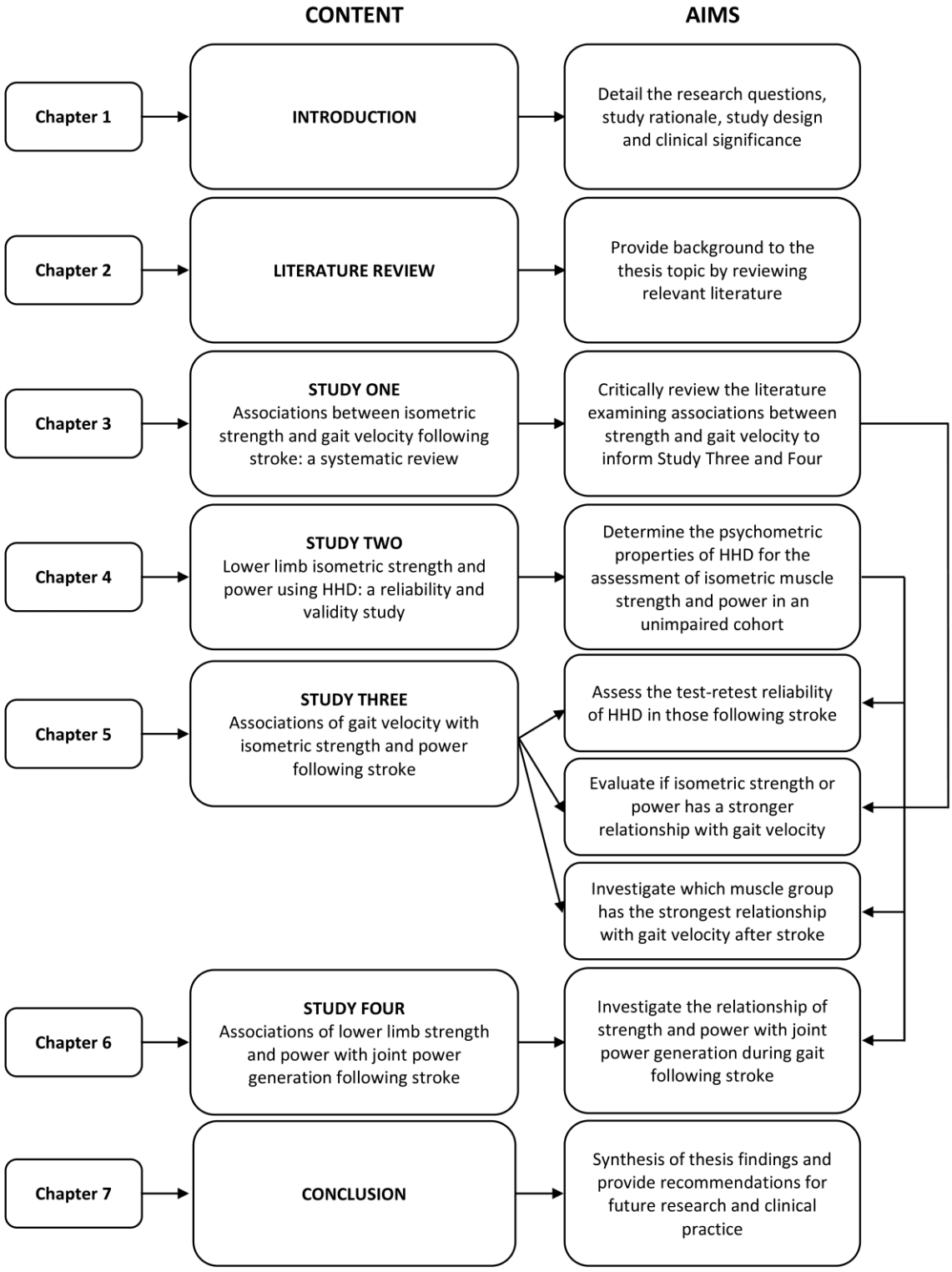

Figure 1.1. Concept map with overview of this thesis. HHD = hand-held dynamometry.

The narrative review of literature contained in Chapter 2 provides the basis for the subsequent studies by identifying the gaps in the previous literature. Upon review of the previous research that examined the associations between isometric strength and gait velocity, it was evident that there was a large volume of research in this area which reported varying correlation values. It was decided to undertake a systematic review in Study One (Chapter 3) to enable the rigorous evaluation of existing studies that reported the associations between lower limb isometric strength and gait velocity following stroke.

1.4.1 Study One: Associations between isometric strength and gait velocity after stroke: a systematic review

Understanding the associations between motor impairments and gait function is important to comprehend the mechanisms of gait and to guide future intervention strategies for individuals following stroke. Previous studies have shown equivocal results in the association between muscle strength and gait velocity depending on the muscle groups assessed and the sample size used (Bohannon, 1986a, 1989b; Dorsch et al., 2012; Ng & Hui-Chan, 2012). Therefore, a systematic review was warranted to critically evaluate the associations between isometric strength and gait velocity in those following stroke. The specific aim of Study One was to systematically review the current literature investigating the associations between isometric muscle strength of individual lower limb muscle groups and gait velocity following stroke. The results from this review helped to inform the design of Study Three and Four. The results from Study One have been published in *Brain Injury* (Mentiplay et al., 2015a).

1.4.2 Study Two: Lower limb isometric strength and power using hand-held dynamometry: a reliability and validity study

Muscle power is often reduced following stroke (Canning, Ada, & O'Dwyer, 1999; Fimland et al., 2011; Gerrits et al., 2009; Knight, Saunders, & Mead, 2014; Pohl et al., 2002; Stavric & McNair, 2012) and has been shown to be more strongly associated with self-reported function, incidence of falls and physical performance than muscle strength in the elderly (Bean et al., 2002; Foldvari et al., 2000; Skelton et al., 2002). Current methods to assess muscle power are either expensive or time demanding, thus limiting their clinical utility. The use of HHDs, accessible and clinically feasible devices, has been shown to provide reliable and valid measures of isometric strength (Bohannon, 2012; Stark, Walker, Phillips, Fejer, & Beck, 2011). Recent iterations of HHDs have allowed the raw force data to be exported relative to time, either during or post assessment. By expressing the raw forces relative to time, it is possible to calculate rate of force development (RFD), also termed 'isometric muscle power' (Mentiplay et al., 2015b). Current HHDs may be an appropriate device to assess isometric muscle power in the clinical setting. Despite the strong reliability and validity of HHD when assessing isometric strength (Bohannon, 2012; Stark et al., 2011), no previous study has examined the ability of these devices to assess isometric muscle power. Additionally, RFD can be calculated using a variety of methods with no consensus in the previous literature as to the most appropriate method. Study Two (Chapter 4) examined the psychometric properties of two models of HHDs for the assessment of isometric strength and RFD in a healthy population. This study also compared the reliability of various algorithms to assess RFD. The results from Study Two supported the use of these devices for the subsequent studies. Study Two has been published in *PLOS ONE* (Mentiplay et al., 2015b).

Study Two involved a concurrent validity, inter-rater and test-retest reliability design to assess the psychometric properties of HHD during the assessment of isometric muscle strength and power in a healthy and unimpaired sample. Specific aims of Study Two were to: 1) examine the reliability of different algorithms for calculation of RFD; 2) assess the test-retest, inter-rater and inter-device reliability of two commercially available HHDs for assessment of isometric lower limb strength and RFD; and 3) determine the concurrent validity of HHD compared with a fixed laboratory-based dynamometer. For this study, a healthy and unimpaired cohort was chosen for numerous reasons. The time and effort demands of these testing sessions warranted the study to be performed in a healthy sample rather than those following stroke. Additionally, the criterion reference of isometric strength and power assessment used in this study involved bulky and cumbersome equipment, which proved challenging to use across multiple lower limb muscle groups even in the unimpaired cohort. To assess two versions of HHD, with two assessors, and multiple lower limb muscle groups also meant that the testing sessions required many maximal contractions. Consequently, Study Two was undertaken in a healthy and unimpaired cohort population prior to the use of HHD in those following stroke for the subsequent studies.

1.4.3 Study Three: Associations of gait velocity with isometric strength and power following stroke

The ability to produce force quickly may provide more insight into gait function following stroke than how much force that muscle can produce. One previous study has shown promising results when comparing measures of strength and power in the stroke population, with isometric RFD having a stronger relationship with gait velocity compared with isometric strength after stroke (Pohl et al., 2002). However, this previous study only examined the strength and power of the knee extensors (Pohl et al., 2002), with other lower

limb muscle groups potentially providing stronger associations with gait velocity. Study Three (Chapter 5) was undertaken to comprehensively examine the relationship between measures of the isometric muscle strength and power of multiple lower limb muscle groups with gait velocity following stroke.

Study Three of this thesis employed an observational, cross-sectional design that incorporated a test-retest reliability component. Specific aims of Study Three were to: 1) comprehensively assess the relationship of isometric lower limb strength and power with gait velocity after stroke; 2) examine which measure (isometric strength or power) explains more of the variance in gait velocity following stroke; and 3) investigate which lower limb muscle group has the strongest relationship with gait velocity after stroke. A secondary aim of Study Three was to assess the test-retest reliability of HHD for assessment of isometric strength and RFD in a stroke cohort. During the first assessment session participants performed tests of gait velocity followed by assessments of isometric strength and power for seven lower limb muscle groups. Participants were invited to attend a second testing session which involved a repeat of the isometric strength and power assessment to determine the test-retest reliability of HHD.

1.4.4 Study Four: Associations of lower limb strength and power with joint power generation following stroke

A key variable that impacts upon gait following stroke is the joint power generated throughout the gait cycle (Kim & Eng, 2004; Olney et al., 1994; Olney et al., 1991). Previous research in healthy populations has shown that the primary muscle groups contributing to joint power generation during gait are the ankle plantarflexors, hip flexors and hip extensors (Liu, Anderson, Pandy, & Delp, 2006; Neptune, Zajac, & Kautz, 2004; Winter, 1983). Deficits in joint power generation can impede the ability to achieve normal gait speeds

following stroke, with studies showing strong correlations between joint power generation during gait and gait velocity in the stroke population (Kim & Eng, 2004; Olney et al., 1994; Olney et al., 1991). Prior research has examined the associations between HHD measured isometric strength and joint power generation in other neurological populations such as cerebral palsy and traumatic brain injury (Dallmeijer et al., 2011; Kahn & Williams, 2015). There is very little information on this relationship in the stroke population and whether measures of isometric muscle power are related to joint power generation during gait.

Study Four (Chapter 6) used an observational, cross-sectional design where participants attended one session in a three-dimensional gait analysis (3DGA) laboratory to examine the relationships of isometric muscle strength and power (as measured with HHD) with joint power generation during the gait cycle following stroke. Specific aims of Study Four were to: 1) examine the relationship between peak ankle, knee and hip joint power generation during gait with corresponding ankle, knee and hip joint measures of isometric strength and power taken from HHD; and 2) inspect which measure, either isometric strength or power, demonstrated a stronger relationship with joint power generation following stroke. The participants involved in Study Four were a subset of those participants included in Study Three.

1.5 Clinical Significance

It is anticipated that the results from this thesis will aid clinicians in the assessment and treatment of their patients through the examination of the reliability and validity of HHD. This could present clinicians and researchers with an accessible and psychometrically-sound device to enhance the objective assessment of isometric muscle strength and power in a clinical setting. The HHDs may show potential to be used in future research as a low cost alternative to the expensive equipment that is currently required for the assessment of

strength and power. Investigation of the relationship between measures of lower limb strength and power with gait could also help to optimise future training techniques in a clinical setting to target different aspects of strength or power. The results from this thesis may also guide interventions to potentially target specific lower limb muscle groups that are shown to be important for gait. Knowledge of this relationship can be used to design intervention strategies to improve strength and power and potentially observe concurrent improvements in gait following stroke.

CHAPTER TWO: LITERATURE REVIEW

This literature review provides the rationale for the four main studies of this thesis. The first section of the review briefly outlines the prevalence and general impairments associated with stroke. The second section explores specific limitations related to gait function and which factors appear to contribute to reduced gait function following stroke. In the third section, a description of the current methods used to assess muscle strength is provided. The third section also encompasses information on how muscle strength relates to gait following stroke. Lastly, a discussion is provided on muscle power, with details about assessment and how muscle power relates to gait. A short conclusion is also provided that outlines how the previous literature identified in this review has informed the design of the studies included in this thesis.

2.1 Stroke prevalence and impairments

2.1.1 Definition and prevalence

A stroke occurs when there is an interruption of the blood supply to the brain through either a blockage (ischaemic) or rupture (haemorrhagic) of the blood vessels within the brain. Ischaemic strokes are more common (approximately 80%) than haemorrhagic strokes (20%) (Australian Institute of Health and Welfare, 2013). Ischaemic strokes can result either from a blood clot forming elsewhere in the body and travelling to the brain (embolic) or from a narrowing of the blood vessels within the brain (thrombotic) (Deloitte Access Economics, 2013). Despite the variations in the types of stroke, there are numerous physical limitations following stroke regardless of the classification.

Stroke is one of the leading causes of disability worldwide (Adamson et al., 2004; Feigin et al., 2014) with an estimated 50,000 Australians suffering a new stroke each year (Deloitte Access Economics, 2013). Mortality rates from stroke have declined in Australia by 70% between 1979 and 2010, which indicates more people are now surviving stroke (Australian Institute of Health and Welfare, 2013). In 2012, over 400,000 Australians were living with stroke in the community (Deloitte Access Economics, 2013). Two thirds of the people who have a stroke are living with post-stroke impairments that hinder their ability to independently perform activities of daily living (Deloitte Access Economics, 2013). The level of disability following stroke is dependent on various factors such as age, comorbidities and the size and location of the brain lesion (Chen, Tang, Chen, Chung, & Wong, 2000; Nichols-Larsen, Clark, Zeringue, Greenspan, & Blanton, 2005). The indirect financial costs of stroke in Australia has been estimated at $5 billion due to lost work hours and the costs associated with health care and carers (Deloitte Access Economics, 2013). With the amount of Australians living with stroke projected to almost double in the next 20 years (Deloitte Access Economics, 2013), stroke (and the associated cardiovascular disease) is considered a national health priority research area by the Australian Government (National Health and Medical Research Council, 2015).

2.1.2 Associated impairments and impact

Stroke can result in both acute and long-term limitations and impairments that may impact on physical function (Duncan et al., 1997). Different limitations or impairments are often present following stroke such as reduced balance (Geurts, De Haart, Van Nes, & Duysens, 2005), increased muscle spasticity (Voerman, Gregorič, & Hermens, 2005) and decreased muscle strength (Bohannon, 1995). The clinical presentation of impairments following stroke is dependent upon the anatomical region of the brain that has been affected. Due to

the large amount of specialisation within the brain, the type of impairment experienced following stroke depends on the neurological function controlled by the affected area (Teasell, Hussein, Viana, Donaldson, & Madady, 2014). Disruption of the blood flow to the cerebral hemispheres, which are supplied by carotid or anterior circulation, often result in impairments such as contralateral weakness (hemiparesis) which can affect gait following stroke (Teasell et al., 2014). Muscle weakness after stroke has been reported to affect the control on one side of the body in approximately 80% of patients (Langhorne, Coupar, & Pollock, 2009). Changes that have been observed following stroke which affect the ability to produce force (muscle weakness) include, but are not limited to, decreases in the number of motor units or abnormal motor unit recruitment (Bourbonnais & Vanden Noven, 1989). This impaired ability to produce force can lead to limitations in gait after stroke (Bohannon, 1989b).

In contrast to cerebral hemisphere strokes, a stroke occurring in the brain stem or posterior hemispheres, including the cerebellum, can lead to different clinical presentations, such as gait ataxia or coordination problems (Teasell et al., 2014). Gait ataxia is characterised by an impaired ability to maintain balance during walking and has often been described as 'drunken' gait due to the resemblance of a person who is intoxicated (Morton & Bastian, 2007). Another common sign of ataxia is a lack of consistency in spatiotemporal aspects of gait such as step length and step time (Palliyath, Hallett, Thomas, & Lebiedowska, 1998). Despite the debilitating effect of gait ataxia (Morton & Bastian, 2007), previous research has indicated that only 2-3% of strokes affect the cerebellum (Edlow, Newman-Toker, & Savitz, 2008; Kelly et al., 2001; Tohgi, Takahashi, Chiba, & Hirata, 1993). Consequently, this thesis will focus on non-cerebellar stroke.

2.2 Gait deficits following stroke

2.2.1 Impact of gait deficits

Impaired gait function is commonly observed following stroke. Previous research has suggested only 50% of people regain the ability to ambulate in the community following stroke (Keenan, Perry, & Jordan, 1984; Perry et al., 1995). Commonly stated rehabilitation goals following stroke include improved ability to perform activities of daily living and, primarily, the attainment of independent walking (Bohannon, Andrews, & Smith, 1988; Kwakkel & Kollen, 2013). An inability to walk independently without the assistance of another person following stroke can hinder participation in activities of daily living and reintegration back into the community. Previous research has shown strong associations between measures of gait and physical activity or community ambulation following stroke (Fulk, Reynolds, Mondal, & Deutsch, 2010; Mudge & Stott, 2009; Robinson, Shumway-Cook, Matsuda, & Ciol, 2011). Participation restrictions and difficulties with community ambulation may lead to a reduced quality of life and self-esteem as well as a potential increased burden of care on relatives and carers. The restoration of walking has long been accepted as a key goal for patients following stroke (Bohannon et al., 1988; Kwakkel & Kollen, 2013). Achieving this goal is reflected by therapists spending the most time during rehabilitation focusing on gait retraining (Latham et al., 2005; Tole et al., 2014). The large amounts of therapy time spent on retraining gait shows this is an important component of rehabilitation after stroke.

2.2.2 Gait velocity after stroke

Different limitations exist in the gait of people following stroke, including changes to lower limb spatiotemporal, kinematic and kinetic variables (Olney & Richards, 1996). The most

commonly assessed spatiotemporal change that occurs to gait after stroke is a reduction in gait velocity compared with unimpaired populations (Lehmann, Condon, Price, & DeLateur, 1987; Nadeau, Betschart, & Bethoux, 2013). Gait velocity is assessed by measuring the time taken to walk a set distance (e.g. 6 or 10 metres) and may be performed at a comfortable or fast pace. Clinically feasible tests that are capable of obtaining measures of gait velocity, such as the 10 Metre Walk Test (Collen, Wade, & Bradshaw, 1990), have shown excellent reliability in the stroke population (Flansbjer, Holmbäck, Downham, Patten, & Lexell, 2005). Gait velocity is a discriminative clinical measure that can be predictive of length of hospital stay, functional outcome and community ambulation (Lord et al., 2004; Perry et al., 1995; Salbach et al., 2001) and has been associated with physical activity levels following stroke (Mudge & Stott, 2009). Therefore, gait velocity receives a large amount of attention in clinical settings during routine assessment, clinical decision making and as an outcome measure for interventions during rehabilitation.

The average self-selected overground gait velocity in stroke populations of various ages (range = 21 to 89 years) has been reported to be between 0.43 to 0.94 m/s depending on the severity and time since stroke (Dettmann, Linder, & Sepic, 1987; Dorsch et al., 2012; Lamontagne, Malouin, Richards, & Dumas, 2002; Lehmann et al., 1987; Lord et al., 2004; Patterson et al., 2007; Roth, Merbitz, Mroczck, Dugan, & Suh, 1997; Severinsen, Jakobsen, Overgaard, & Andersen, 2011; Von Schroeder, Coutts, Lyden, Billings Jr, & Nickel, 1995). In comparison, healthy populations of similar ages (range = 24 to 79 years) have been reported to walk at speeds between 0.99 to 1.40 m/s (Dettmann et al., 1987; Lamontagne et al., 2002; Lehmann et al., 1987; Sofuwa et al., 2005; Von Schroeder et al., 1995). Additional assessments of gait velocity can be performed whilst asking the participant to walk as fast as possible, often termed fast paced gait. Fast gait speed may provide augmented information as the ability to increase gait velocity may better reflect physical function than self-selected

comfortable speed (Dobkin, 2006). Following stroke, average fast paced gait velocity has been reported to be between 0.61 to 1.09 m/s (Davies, Mayston, & Newham, 1996; Hsu, Tang, & Jan, 2003; Jonsdottir et al., 2009; Kobayashi, Leung, & Hutchins, 2011; Nadeau, Gravel, Arsenault, & Bourbonnais, 1999b; Nadeau, Gravel, Arsenault, Bourbonnais, & Goyette, 1997; Nakamura et al., 1985), which is still impaired compared with the self-selected velocity of unimpaired individuals (0.99 to 1.40 m/s) (Dettmann et al., 1987; Lamontagne et al., 2002; Lehmann et al., 1987; Sofuwa et al., 2005; Von Schroeder et al., 1995). However, variation between individuals following stroke is large, with one previous study of 50 community dwelling adults 6 to 46 months following stroke reporting a range of fast paced velocities from 0.50 to 2.20 m/s (Flansbjer et al., 2005). Despite the high variability in gait speeds in persons following stroke, gait velocity is used to provide an indication of overall gait performance in stroke (Teixeira-Salmela et al., 2001).

One of the key goals of rehabilitation is to achieve a walking speed that allows for community ambulation. A seminal research study stated a velocity of 0.80 m/s is required to be able to safely walk in the community (Perry et al., 1995). This speed of 0.80 m/s is similar to that of previous research that has assessed the requirements of safely crossing intersections in the community (Hoxie & Rubenstein, 1994), although the speed requirements for intersection crossing varies depending on the country assessed, with results between 0.44 and 1.32 m/s across Australia, Singapore and the United States of America (Salbach et al., 2014). Gait velocity is an important variable that is often assessed for clinical decision making and will be a major focus of this thesis.

2.2.3 Spatiotemporal, kinematic and kinetic changes after stroke

Due to the unilateral impairments following stroke (on the contralateral side of the body to the brain lesion), stroke results in changes in gait that are often asymmetrical (Kim & Eng,

2004), which may contribute to a reduced gait velocity. Compensatory strategies often seen during gait following stroke include forefoot landing, hip circumduction, pelvic hiking and knee hyperextension (Chen, Patten, Kothari, & Zajac, 2005; Kim & Eng, 2004; Lehmann et al., 1987). A common feature of gait following stroke is the increased variability of spatiotemporal parameters between steps, with research showing increased variability in step length, stride time and swing time compared to the unimpaired population (Balasubramanian, Neptune, & Kautz, 2009). The affected or paretic side often displays reduced step length and cadence compared with healthy populations (Dettmann et al., 1987; Lehmann et al., 1987), whilst the unaffected or non-paretic limb spends a longer time in stance phase and consequently the paretic limb spending longer time in swing (Dettmann et al., 1987; Lin, Yang, Cheng, & Wang, 2006; Von Schroeder et al., 1995).

Gait after stroke is also characterised by changes in kinematic (e.g. joint range of motion) variables (Chen et al., 2005; Kim & Eng, 2004; Lamontagne et al., 2002). Examination of the kinematic and kinetic changes that occur following stroke can provide more detailed measures of gait impairments compared to spatiotemporal variables. Alterations to the kinematic movement patterns following stroke include a reduction in joint range of motion in the sagittal plane at the hip, knee and ankle of the paretic limb (Kim & Eng, 2004). Examples of the kinematic changes following stroke are a reduction in knee flexion at toe off (Chen et al., 2005) and reduced dorsiflexion during the swing phase of gait (Lamontagne et al., 2002) in the paretic limb in comparison with the unimpaired population. Both of these kinematic deficits impair ground clearance of the foot during gait and can potentially result in proximal compensation strategies such as hip circumduction or pelvic hiking to avoid the foot catching on the ground during swing.

2.2.4 Joint power generation during gait after stroke

Kinetic variables, such as joint moments and power, are often affected following stroke (Kim & Eng, 2004; Nadeau et al., 2013; Olney & Richards, 1996). An important measure of gait function following stroke is the power generated throughout the gait cycle (Kim & Eng, 2004; Olney et al., 1991; Olney & Richards, 1996). The power generated throughout the gait cycle is calculated by multiplying the joint moments by joint angular velocity (Winter, 1983). Power generation during gait provides an indication of the power produced for forward propulsion. Evidence suggests that peak joint power generation events during gait are reduced in those following stroke compared to a healthy population (Olney & Richards, 1996), reduced on the paretic compared to non-paretic side (Kim & Eng, 2004) and are also decreased in those with stroke who walk slower (Olney et al., 1991). Deficits in joint power events during gait can impede the ability to achieve healthy gait speeds, with studies showing strong relationships between joint power generation during gait and gait velocity following stroke (Kim & Eng, 2004; Olney et al., 1994; Olney et al., 1991). Research has shown joint power generation variables to be more strongly correlated with gait velocity than kinematic variables (Kim & Eng, 2004), therefore, power generation may be a more informative measure of gait following stroke than other variables such as kinematics.

Studies have shown that the main muscle group contributing to forward progression in unimpaired populations is the ankle plantarflexors (Kepple, Siegel, & Stanhope, 1997; Liu et al., 2006). During the push off phase of gait these muscles account for 80-85% of the power generated during the entire gait cycle (Winter, 1983). The hip flexors and hip extensors have also been reported as key muscle groups for generating forward progression (Liu et al., 2006; Neptune et al., 2004). Figure 2.1 provides the profiles for sagittal plane

joint power from an unimpaired, healthy participant during walking. The majority of the power generated in the lower limb during gait occurs in the sagittal plane (Eng & Winter, 1995). Increasing the power generated at each of the three main power generation events during gait (at A2, H1 and H3 in Figure 2.1) may lead to improved gait velocity by improving forward progression of the limb, and therefore enhance functional recovery after stroke.

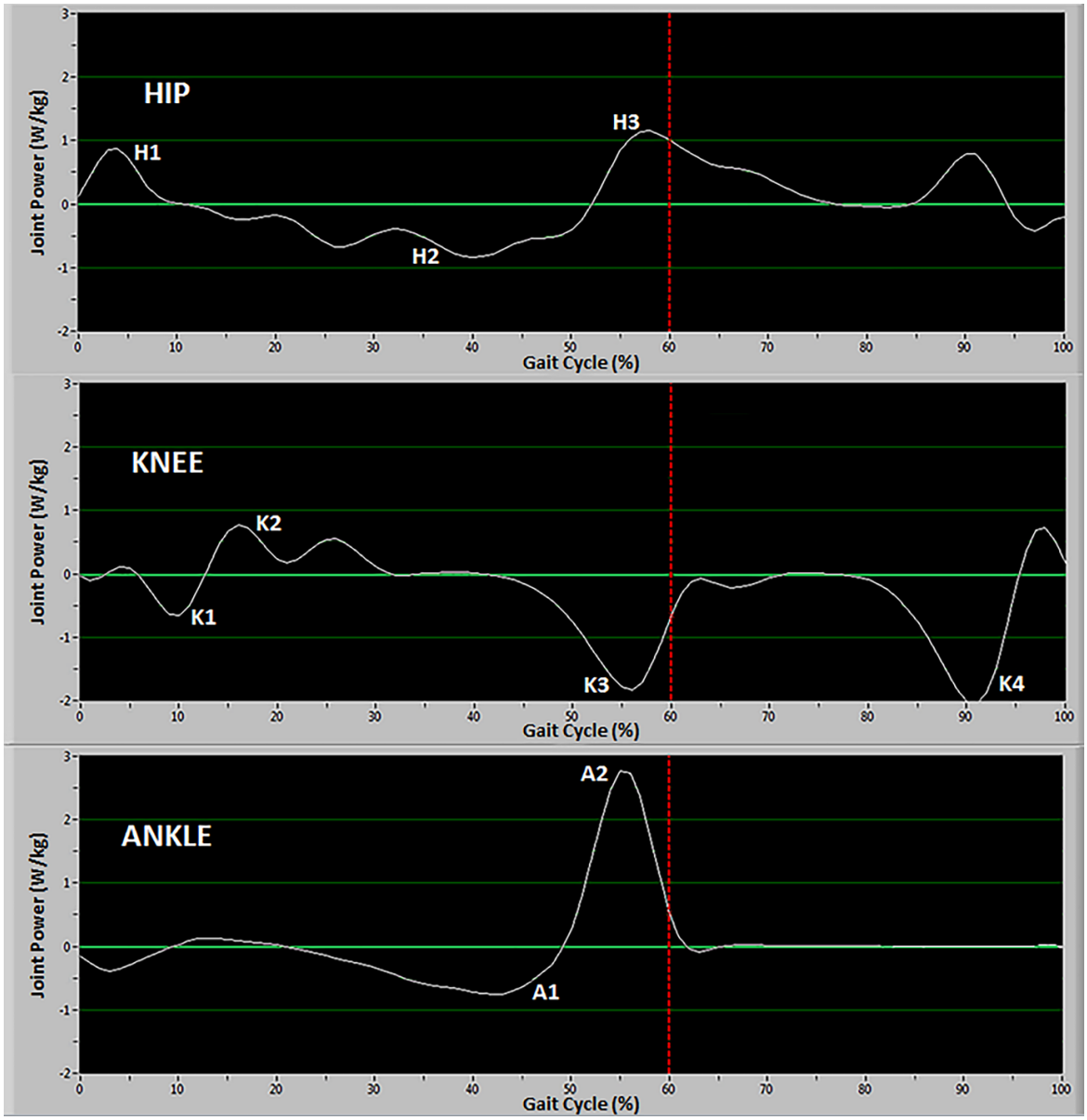

Figure 2.1. Lower limb sagittal plane joint power profiles of an unimpaired gait pattern. Data have been time normalised to 100% of the gait cycle. Positive power indicates power generation (concentric contractions), negative power indicates absorption (eccentric contractions). The dashed vertical line represents toe off. The largest power generation event occurs at A2 (ankle plantarflexors prior to toe off/pre-swing). The second largest power generation events occur at H3 (hip flexors at toe off/pre-swing), followed by H1 (hip extensors just after initial contact/loading response). The knee extensors provide a small generation of power at K2 (knee extensors during mid stance). Power absorption events occur at A1 (ankle plantarflexors as the leg rotates over the foot during mid to terminal stance), K1 (knee extensors just after initial contact/loading response), K3 (knee extensors to control knee flexion at toe off/pre-swing), K4 (knee flexors during terminal swing) and H2 (hip flexors during mid to terminal stance).

Changes in joint power generation have been examined previously to determine how this measure impacts on gait function following stroke. A cross-sectional study of 12 people following stroke and 10 healthy controls examined how joint power generation changed with increasing gait velocities and compared the results between the stroke cohort and the control group (Jonkers, Delp, & Patten, 2009). This study asked participants to walk at a self-selected comfortable speed and then a fast paced speed across a 3DGA laboratory. The study by Jonkers et al. (2009) showed that high functioning stroke patients, defined as being able to walk at a self-selected speed above 50% of the self-selected speed of healthy controls, used similar strategies to increase gait speed to those of the healthy controls by increasing ankle plantarflexor power generation (A2 in Figure 2.1) and hip flexor power generation (H3 in Figure 2.1) of the paretic limb (Jonkers et al., 2009). However, the lower functioning stroke patients, defined as being unable to walk at a self-selected speed above 50% of the self-selected speed of healthy controls, failed to increase ankle plantarflexor or hip flexor power generation in their paretic limb to increase gait speed (Jonkers et al., 2009). Lower functioning patients increased gait speed through increases in power generation of the non-paretic limb (Jonkers et al., 2009), which may have undesirable consequences for the non-paretic limb such as increasing fatigue or injury risk. Another cross-sectional study (n = 17) showed that post-stroke individuals preferentially increased the utilisation of hip muscles over ankles to increase gait velocity (Milot, Nadeau, & Gravel, 2007). The results of these prior studies show that following stroke lower functioning individuals lack power generation of the paretic limb when increasing velocity (Jonkers et al., 2009), and that ankle plantarflexor power generation is affected more so than proximal muscle groups (Milot et al., 2007). Therefore, increasing power generation, especially around the ankle, may be an important rehabilitation consideration for clinicians when developing treatment plans to improve gait velocity.

Previous studies in stroke have examined the ability of different types of interventions to improve power generation and shown subsequent improvements in gait velocity (Brincks & Nielsen, 2012; Parvataneni, Olney, & Brouwer, 2007; Teixeira-Salmela et al., 2001). One single-group, six-week gait retraining study of 13 post-stroke individuals showed significant increases in ankle plantarflexor (A2 in Figure 2.1), hip extensor (H1 in Figure 2.1) and hip flexor (H3 in Figure 2.1) power generation on the paretic side (Brincks & Nielsen, 2012). These improvements in power generation demonstrated significant correlations with improvements in gait velocity post intervention (Spearman's rho = 0.71 to 0.86) (Brincks & Nielsen, 2012). Another single-group interventional study of 13 individuals after stroke examined the effects of a 10-week combined program of muscle strengthening and physical conditioning on gait performance (Teixeira-Salmela et al., 2001). Post intervention, a significant increase in gait velocity was observed which coincided with higher levels of power generation of the ankle plantarflexor, hip extensor and hip flexor muscle groups (Teixeira-Salmela et al., 2001). The results from these intervention studies demonstrate that increases in gait velocity can correspond with increases in ankle and hip power generation during gait, which reinforces the importance of potentially addressing joint power generation in rehabilitation after stroke.

2.2.5 Factors that contribute to reduced gait function after stroke

Identification of key variables that relate to and affect gait is important to build a better understanding of the mechanisms of impaired gait and to guide future intervention strategies. The main focus of this thesis will be on the relationship between muscle strength and gait after stroke, however other factors may contribute to reduced gait function following stroke, such as reduced balance (Bohannon, 1987, 1989b; Nadeau, Arsenault, Gravel, & Bourbonnais, 1999a; Suzuki, Imada, Iwaya, Handa, & Kurogo, 1999; Suzuki, Nakamura,

Yamada, & Handa, 1990) or lower limb muscle spasticity (Bohannon, 1987; Bohannon & Andrews, 1990; Hsu et al., 2003; Nadeau et al., 1999a). Static standing balance has shown moderate to very strong correlations with gait velocity following stroke (correlation values = 0.42 to 0.90) depending on the methods used to assess balance and the stroke severity of included participants (Bohannon, 1987, 1989b; Nadeau et al., 1999a; Suzuki et al., 1999; Suzuki et al., 1990). Reduced balance is often a result of a range of multifactorial limitations including muscle weakness or reduced proprioception. Therefore, investigation of the relationship between other distinct variables and gait function may provide a stronger insight into gait impairments.

Previous research has examined the relationship between lower limb spasticity and gait velocity after stroke (Bohannon, 1987; Bohannon & Andrews, 1990; Hsu et al., 2003; Nadeau et al., 1999a). Results have shown spasticity in the ankle plantarflexors and knee extensors has very weak to moderate correlations with gait velocity following stroke (correlation values = -0.01 to -0.47) (Bohannon, 1987; Bohannon & Andrews, 1990; Hsu et al., 2003; Nadeau et al., 1999a) suggesting there is a limited association between spasticity and gait velocity (Williams, Banky, & Olver, 2015). Lower limb spasticity may impact upon gait, although more research is needed.

It may be pertinent to examine other factors, such as muscle strength as it appears to have a greater influence on gait following stroke. Despite previous research examining the relationships between different variables and gait following stroke, this thesis will focus on the relationships between components of muscle function, including muscle strength, and gait function following stroke.

2.3 Muscle strength and gait

2.3.1 Assessment of muscle strength

Assessment of muscle strength can be done through numerous indirect and direct methods. Indirect measures of muscle strength generally consist of functional performances that are anticipated to relate to muscle strength. Previously utilised indirect tests include the single leg calf raise test (Hébert-Losier, Newsham-West, Schneiders, & Sullivan, 2009; Lunsford & Perry, 1995; Maurer, Finley, Martel, Ulewicz, & Larson, 2007) and the five times sit-to-stand test (Csuka & McCarty, 1985; Guralnik et al., 1994). These indirect tests of muscle strength are clinically feasible and require minimal equipment. However, poor to moderate correlations have been found between the time taken to perform the sit-to-stand test and direct isometric measures of the muscle strength of various lower limb muscle groups in the stroke population (Mong, Teo, & Ng, 2010). As such, direct measures are more commonly utilised to provide informative data on muscle strength.

A commonly used direct method of strength assessment in the athletic population involves determining a one-repetition maximum (1RM) of different exercises such as the leg press or knee extension (McMaster, Gill, Cronin, & McGuigan, 2014). Assessment of 1RM has been used previously in the stroke population to assess changes in muscle strength pre and post intervention (Hill et al., 2012; Ouellette et al., 2004; Weiss, Suzuki, Bean, & Fielding, 2000), however this method has limitations. Due to the maximal exertion during testing, a large amount of time is needed for warm up, rest breaks and progressive weight increases. The time demands of 1RM assessment typically preclude the use of this type of strength testing in routine clinical assessment of people with impairments. Additionally, these assessments often provide a single strength measure of a combination of multiple lower limb muscle groups (e.g. leg press), with no indication of how each individual muscle group is working

during the exercise and therefore does not assess the contribution of each muscle group to task performance. The 1RM of single muscle groups can be performed (e.g. knee extension), however to provide a comprehensive assessment of multiple lower limb muscle groups, a large amount of time is required if using 1RM testing techniques. Determination of the strength of individual muscle groups may be important to clinicians to understand the impairments associated with stroke and to focus on appropriate rehabilitation strategies to target the most important muscle groups for improvement.

Laboratory-based fixed dynamometry is often referred to as the 'gold standard' for strength assessment (Stark et al., 2011), which allows for measurements in both an isometric (same muscle length) and isokinetic mode (moving at a constant velocity). Dynamometry is able to provide strength measures on either side of the body of individual muscle groups (e.g. left hamstring strength). Isokinetic testing involves a maximal voluntary contraction (MVC) whilst the limb is moved at a constant velocity through the full (or close to full) range of motion of a particular joint. Whilst isokinetic testing has been used previously in the stroke population for both cross-sectional and intervention studies (Carvalho, Sunnerhagen, & Willén, 2013; Eng, Chu, Dawson, Kim, & Hepburn, 2002a; Flansbjer, Downham, & Lexell, 2006; Flansbjer, Miller, Downham, & Lexell, 2008; Hsu et al., 2003; Kim, Eng, MacIntyre, & Dawson, 2001), it has shown mixed reliability when assessing people following stroke depending on the muscle group assessed and velocity of movement (intraclass correlation coefficients (ICCs) = 0.44 to 0.99) (Eng, Kim, & MacIntyre, 2002b; Hsu, Tang, & Jan, 2002; Pohl, Startzell, Duncan, & Wallace, 2000). Additionally, isokinetic testing is limited to the use of laboratory-based equipment, with no clinically accessible alternative available.

Isometric testing involves an MVC where the muscle stays at the same length and joint angle against unyielding resistance. The procedure involves the participant performing an MVC

over a short period of time. The peak amount of force recorded during the trial (peak force) is then used as the outcome measure to indicate muscle strength (see Figure 2.2). Peak force can be measured in Newtons, kilograms or pounds and is usually then converted to torque by multiplying the force value by the length of the lever arm (i.e. distance between dynamometer and joint centre). Torque is usually measured in Newton metres (Nm). Both force and torque are often used interchangeably within the literature related to muscle strength, although it should be noted they refer to similar yet distinct constructs. An additional step in the calculation of isometric strength is to normalise to body mass. This is done by dividing the torque by body mass to indicate the strength relative to body mass (Nm/kg). The additional step of normalisation has been used previously when examining relationships between isometric strength and gait kinetics (Dallmeijer et al., 2011). Regardless of the terminology used, isometric strength has shown excellent reliability for the upper and lower limbs in the stroke population using various dynamometers (reliability coefficients = 0.81 to 0.99) (Bertrand, Mercier, Bourbonnais, Desrosiers, & Grave, 2007; Bohannon, 1986b, 1990; Bohannon & Walsh, 1992) and is commonly used in research for both cross-sectional and intervention designs (Dorsch et al., 2012; Duncan et al., 2003; Liu-Ambrose et al., 2007; Ng & Hui-Chan, 2012; Severinsen et al., 2011). Despite the strong psychometric properties, laboratory-based fixed dynamometers are typically expensive and involve cumbersome equipment which precludes their use in the clinical environment (Marmon, Pozzi, Alnahdi, & Zeni, 2013; Moriello & Mayo, 2006).

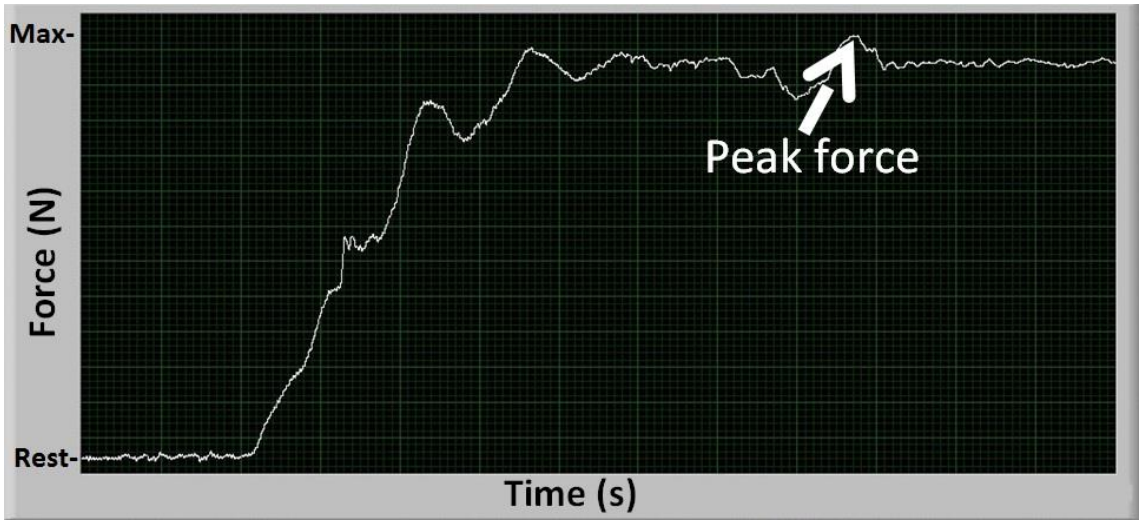

Figure 2.2. Raw force trace for assessment of isometric muscle strength from a maximal voluntary contraction against a dynamometer. The arrow shows the point of peak force used for strength assessment.

Due to the limitations in using laboratory-based fixed dynamometry, clinicians have previously used subjective rating scales to assess the isometric strength of their patients, such as manual muscle testing (Bohannon, 2005). Manual muscle testing involves an assessor rating the force applied by individual muscle groups using a Likert-type scale from 0 to 5. Although this type of testing is clinically feasible, and has demonstrated acceptable reliability (Cuthbert & Goodheart Jr, 2007), manual muscle testing using a subjective rating scale has shown limited adequacy as a clinical test due to poor sensitivity and specificity (Bohannon, 2005, 2010). Devices that combine the accuracy of fixed dynamometers and the clinically accessible nature of manual muscle testing are needed for clinicians and researchers to use in the assessment of isometric muscle strength.

Clinically feasible devices that have been commonly used to measure lower limb isometric muscle strength are HHDs. These devices have been reported to be the most appropriate and convenient method of assessing muscle strength in a clinical setting due to their low cost, portable nature and strong reliability in a range of clinical populations (Moriello & Mayo,

2006; Stark et al., 2011). Additionally, HHD has shown good validity when compared to expensive laboratory-based dynamometers (Stark et al., 2011). The assessment of isometric strength using HHDs is performed in the same manner as laboratory-based dynamometry which provides an immediate absolute measure of strength (i.e. peak force). Prior research studies have used HHD many times in the stroke population (Bohannon, 1986b; Dorsch et al., 2012; Lin et al., 2006; Liu-Ambrose et al., 2007). Due to the limitations with fixed dynamometry and other measures of muscle strength, HHD will be the focus of this thesis.

The use of HHD is widespread and a number of variations of the device exist, with a recent systematic review identifying 13 different models of HHDs used in published research (Bohannon, 2012). To date, more than 10 different HHDs have been used in previous research and each of these devices vary with respect to their sampling rates, design and output of results. Current versions of HHD involve strain-gauge load cells with digital displays that provide the clinician with an instantaneous measure of muscle strength (peak force, as shown in Figure 2.2). The procedures employed for use of HHDs also varies widely in previous research (Bohannon, 2012; Stark et al., 2011). Differences exist in the number of trials recorded, the duration of each contraction, the rest period between trials, the placement of the dynamometer pad and the position of the participant during testing. Assessment with HHD can involve either 'break' or 'make' tests. A break test involves a slow increase in force by the assessor until they are able to 'break' or overcome the force of the participant. The use of break tests is contentious for many reasons, including differences between scores from different assessors (Bohannon, 2012). Another limitation of the break test is the assessor is required to produce more force than the participant, which may not be possible during the assessment of larger muscle groups (e.g. knee extensors). The make test is more commonly used and involves the participant producing their maximal force while the HHDs are held stationary by the assessor. The make test has been shown to have stronger

reliability than the break test (Kolber & Cleland, 2005; Stratford & Balsor, 1994). Despite all the variations in the literature surrounding methodology, clinicians require a testing protocol that can be implemented with ease in clinical populations such as the elderly or neurological conditions.

Supporting the use of HHD as a clinically feasible alternative to laboratory-based dynamometry are the results from three previous reviews which found excellent intra-rater reliability as well as concurrent validity when compared with laboratory-based dynamometers (Bohannon, 2012; Kolber & Cleland, 2005; Stark et al., 2011). However, one of the previous reviews demonstrated equivocal inter-rater reliability of HHDs with ICCs between -0.04 and 0.99 (Bohannon, 2012), depending on the assessor characteristics, the muscle group assessed and the population tested. Interestingly, 65% of the ICCs reported in the systematic review by Bohannon (2012) were at least 0.80, indicating good to excellent inter-rater reliability (Bohannon, 2012). It was also noted that higher reliability (for both intra- and inter-rater) was found in clinical populations, who have impaired strength levels, compared with healthy controls (Bohannon, 2012). One of the included studies within the previous review by Bohannon (2012) in particular highlights this, with higher inter-rater reliability shown across various lower limb muscle groups in patients with neuropathic weakness (ICCs = 0.86 to 0.97) compared to a healthy control group (ICCs = 0.38 to 0.92) (Kilmer et al., 1997). The lower inter-rater reliability in healthy controls suggests that assessor strength may be an important component of HHD testing due to the lower consistency of results shown in those with higher levels of strength (i.e. healthy population). However, the reduced inherent variability of the healthy population may have also resulted in lower inter-rater reliability.

Previous research has compared the assessment results of HHD of unimpaired populations when performed by assessors of different genders, age, experience, height and weight (Kelln, McKeon, Gontkof, & Hertel, 2008; Krause et al., 2014; Wikholm & Bohannon, 1991). Early research of clinical populations conducted by Bohannon and colleagues examined the inter-rater reliability of HHD (Bohannon & Andrews, 1987; Bohannon, Smith, Hull, Palmeri, & Barnhard, 1995) and showed excellent inter-rater reliability for lower limb muscle strength with correlation coefficients $\geq$ 0.84, however limited descriptions of the assessor anthropometrics and experience were provided (Bohannon & Andrews, 1987; Bohannon et al., 1995). Another early study by Wikholm and Bohannon (1991) in a healthy population showed poor inter-rater reliability of the knee extensors between three assessors, with varying strength levels and body weights. This study also noted that one assessor recorded almost double the peak force of the other two assessors for the strength of the knee extensors (Wikholm & Bohannon, 1991), indicating that the exact strength values of participants from different assessors may not be transferrable. A more recent study by Krause et al. (2014) of a healthy population used three assessors with a range of experience, strength levels, height and weight and showed moderate to excellent inter-rater reliability when testing muscles around the hip. Excellent inter-rater reliability was found even with assessors recording differing peak force values (Krause et al., 2014), which again indicates that the exact results from different assessors may not be transferrable between assessors. Another study in the healthy population by Kelln et al. (2008) examined muscle groups around the hip, knee and ankle and demonstrated excellent inter-rater reliability between three assessors of differing experience, height and weight. In contrast to the study by Krause et al. (2014), the study by Kelln et al. (2008) revealed that all three assessors recorded similar peak force values. The equivocal results between inter-rater reliability studies may be in part due to the strength of the assessors but also of the individuals tested. Despite concerns being

raised over assessor strength, HHD is currently considered the most appropriate and convenient method of assessing muscle strength in a clinical setting (Moriello & Mayo, 2006; Stark et al., 2011). The relatively inexpensive and portable HHD is commonly used and the majority of studies have shown excellent reliability and validity, compared to fixed dynamometry, in a range of populations (Bohannon, 2012; Kolber & Cleland, 2005).

The relationship between the strength of individual lower limb muscle groups and gait can provide an insight into which muscles influence gait and hence, which muscles may be targeted for assessment and rehabilitation following stroke. The following sections of this thesis examine the associations between isometric muscle strength and gait measured in both a clinical and laboratory setting following stroke. The main focus of the information presented on the clinical measurement of gait will be on gait velocity due to the ease of assessment and importance of this variable in predicting length of hospital stay, functional outcome and community ambulation (Lord et al., 2004; Perry et al., 1995; Salbach et al., 2001). Previous studies have examined associations between gait velocity and other measures of muscle strength such as 1RM testing (Weiss et al., 2000) and isokinetic assessment of muscle strength (Eng et al., 2002a; Flansbjer et al., 2006; Hsu et al., 2003; Patterson et al., 2007; Suzuki et al., 1999). However, there are limitations in these forms of testing; therefore, the focus of this thesis will be on clinically feasible isometric strength assessment. The laboratory measurement of gait used in this thesis will be joint power generation during gait, which has been shown to be more strongly associated with gait velocity than other laboratory-based measures such as kinematic variables (Kim & Eng, 2004) and is able to differentiate between high and low functioning stroke patients (Jonkers et al., 2009).

2.3.2 Associations between isometric muscle strength and gait velocity

The measurement of isometric lower limb peak force has been correlated with gait velocity after stroke in numerous prior studies (Bohannon, 1986a; Bohannon & Andrews, 1990; Dorsch et al., 2012; Severinsen et al., 2011) in an attempt to better understand this relationship and inform the development of targeted intervention strategies. The most commonly assessed muscle group of the lower limb following stroke is the knee extensors, with many research studies examining the strength of this muscle group in the stroke population (Bohannon, 1991; Bohannon & Walsh, 1992; Kobayashi et al., 2011; Lam, Lau, Chan, & Sykes, 2010; Maeda, Yuasa, Nakamura, Higuchi, & Motohashi, 2000; Pang & Eng, 2008; Pang, Eng, Dawson, McKay, & Harris, 2005; Severinsen et al., 2011; Suzuki et al., 1999). Despite the popularity of knee extensor strength as a variable, equivocal correlation results have been found between the isometric strength of the knee extensors and gait velocity following stroke (Bohannon, 1986a, 1989b; Bohannon & Walsh, 1992; Dorsch et al., 2012; Liu-Ambrose et al., 2007; Severinsen et al., 2011).

Preliminary research examining the associations between isometric strength and gait velocity following stroke started approximately 30 years ago with Bohannon and colleagues publishing many studies in the area (Bohannon, 1986a, 1989a, 1989b, 1991, 1992; Bohannon & Andrews, 1990; Bohannon & Walsh, 1992). The association between the strength of the knee extensors and gait velocity showed mixed results with correlation coefficients ranging from 0.36 to 0.81 (Bohannon, 1986a, 1989a, 1989b, 1991, 1992; Bohannon & Andrews, 1990; Bohannon & Walsh, 1992). Bohannon's early research used both HHD and laboratory-based devices and measured gait velocity at both self-selected and fast paced speeds, with no apparent difference in correlations based on the device used or pace of gait assessment. Additionally, the Bohannon studies included relatively small

sample sizes (of between 12 to 33 participants), which suggests that the results from this work should be interpreted with caution due to the studies potentially being underpowered to detect a significant association (Portney & Watkins, 2009).

More recent studies with larger sample sizes (of between 45 and 63 participants) show a clear trend towards a weak to moderate association between knee extensor strength and gait velocity following stroke (correlation coefficients = 0.27 to 0.55) (Dorsch et al., 2012; Lam et al., 2010; Liu-Ambrose et al., 2007; Severinsen et al., 2011). Additionally, a recent systematic review identified that the majority of strength training interventions in neurological rehabilitation have focussed on training the knee extensors, and that the majority of these interventions have failed to result in significant improvements in gait (Williams, Kahn, & Randall, 2014b). This combination of ineffective interventions and modest associations between knee extensor strength and gait velocity indicates little importance of this muscle group in walking after stroke, and therefore it may be more pertinent to examine other lower limb muscle groups.

It would seem logical that the strength of the muscle groups that produce the largest joint power generation events during gait, the ankle plantarflexors, hip flexors and hip extensors, would provide a stronger correlation with gait velocity than the knee extensors, which play a limited role in forward progression. Limited high quality research with large participant numbers exists that examines the associations between the strength of either the ankle plantarflexors, hip flexors or hip extensors muscle groups and gait velocity following stroke. Research with relatively low sample sizes (n = 12 to 33) has shown mixed results in the correlation between the strength of the ankle plantarflexors and gait velocity (correlation coefficients = 0.25 to 0.83) (Bohannon, 1986a, 1989b; Nadeau et al., 1997; Nasciutti-Prudente et al., 2009). The few studies with a larger sample size (n = 60 to 68) seem to show

a clear trend towards a weak to moderate correlation (correlation coefficients = 0.29 to 0.58) (Dorsch et al., 2012; Lin et al., 2006; Ng & Hui-Chan, 2012), despite the importance of the ankle plantarflexors in generating forward progression during gait. A small amount of research exists examining the isometric strength of the hip flexors and extensors and their correlation with gait velocity. Mixed results have been found for the hip flexors and hip extensors with correlation values ranging from 0.25 to 0.82 and 0.29 to 0.78 respectively, with variation in regards to the sample size used across the studies (n = 12 to 60) (Bohannon, 1986a, 1989b; Dorsch et al., 2012; Lin, 2005; Nasciutti-Prudente et al., 2009). Of these previous studies, the largest study that examined the strength of the hip flexors and hip extensors (n = 60) found weak correlations of 0.35 and 0.29 for the hip flexors and extensors respectively (Dorsch et al., 2012). Due to the small number of studies with a large sample size that have examined the association between gait velocity and the ankle plantarflexors, hip flexors and hip extensors, further research is warranted to investigate these potentially important muscle groups.

Other lower limb muscle groups that have been assessed previously for strength include the knee flexors, hip abductors and ankle dorsiflexors. As with the previously mentioned muscle groups, limited research assessing the correlation between the strength of the knee flexors and hip abductors with gait velocity exists with large sample sizes. One article published by Dorsch et al. (2012) (n = 60) found weak correlations of 0.30 and 0.24 for the knee flexors and hip abductors respectively (Dorsch et al., 2012). In contrast, the association between ankle dorsiflexor strength and gait velocity has shown consistently moderate to strong results (correlation coefficients = 0.50 to 0.77), regardless of the sample size used (n = 12 to 68) (Bohannon, 1986a, 1989b; Dorsch et al., 2012; Lin et al., 2006; Lin, 2005; Nasciutti-Prudente et al., 2009; Ng & Hui-Chan, 2012). The ankle dorsiflexors act during the swing phase of gait to help with ground clearance of the foot (Whittle, 2002; Winter, 1991).

Weakness of the ankle dorsiflexors can lead to compensatory movements, such as leg circumduction or pelvic hiking, to allow for foot clearance during gait (Whittle, 2002; Winter, 1991), therefore increasing swing time and potentially resulting in a reduction in overall gait velocity (Dorsch et al., 2012). The strength of the ankle dorsiflexors following stroke may play a more important role in determining gait velocity than previously thought. However, further research of multiple lower limb muscle groups (not just the knee extensors) is still needed with larger sample sizes to determine the interactions between isometric strength and gait velocity.

Due to the large amount of research and heterogeneity between studies that have examined the relationship between isometric strength and gait velocity following stroke, a synthesis of previous correlational studies would provide an insight into which muscle group has the strongest association with gait velocity. However, prior to this thesis, no systematic review of previous literature has been performed. Further research is needed to determine which muscle group is most strongly associated with gait velocity, to help determine which muscle groups should be assessed and potentially trained to optimise functional recovery following stroke. Study One (Chapter 3) of this thesis includes a systematic review of the literature further examining the correlations between lower limb isometric muscle strength and gait velocity following stroke.

2.3.3 Associations between isometric muscle strength and joint power generation during gait

Limited research exists that has examined the associations between clinically feasible measurements of any physical function variable (e.g. strength, balance, observational gait measures) and joint power generation throughout the gait cycle in the stroke population. Two previous studies have used observational gait analysis to measure ankle power

generation (APG) during gait in two cohorts of 11 people following stroke (McGinley, Goldie, Greenwood, & Olney, 2003; McGinley, Morris, Greenwood, Goldie, & Olney, 2006). During these studies, therapists used two 11-point rating scales from 0 to 10 (one 'normal' scale and one 'abnormal' scale) to grade APG at push off during gait. One study performed observations from recorded video tapes from a sagittal perspective (McGinley et al., 2003) and one in a clinical setting where the observers used various viewing angles (McGinley et al., 2006). The observers were required to score the ankle plantarflexor power generation on the rating scales from 0 to 10 resulting in 22 possible ratings, where higher scores suggested higher levels of APG. The study with recorded video tapes performed reliability analysis from a second round of assessments four weeks later and found acceptable intra-rater and inter-rater reliability for the scales with ICCs of 0.89 and 0.76 respectively (McGinley et al., 2003). Additionally, very strong correlations were found between the observational gait analysis scores and 3DGA measurements of APG during gait (correlation coefficients = 0.84 to 0.98) (McGinley et al., 2003; McGinley et al., 2006). Whilst demonstrating promising results of measuring APG using observational gait analysis, these two studies were performed on small sample sizes (n = 11) suggesting further research is required to determine the accuracy, sensitivity and responsiveness of these clinical observations. Additionally, as joint power generation has shown strong associations with gait velocity following stroke (Kim & Eng, 2004; Olney et al., 1994; Olney et al., 1991), the observers may have been rating participants on how quickly the participants were walking rather than the actual power generation at the ankle joint, which may be a difficult measure to assess visually. Future research may need to assess other measured variables to examine the relationship with joint power generation.

Studies in other neurological populations (cerebral palsy and traumatic brain injury) have examined the associations between isometric strength measured with HHD and joint power

generation during gait (Dallmeijer et al., 2011; Kahn & Williams, 2015). A recent article by Kahn and Williams (2015) measured the isometric strength of the ankle plantarflexors using HHD and examined the relationship with peak APG during gait in people following traumatic brain injury (Kahn & Williams, 2015). Due to the lack of clinically feasible measures of joint power generation during gait, the study by Kahn and Williams (2015) was undertaken to determine whether HHD could be used to provide an indication of APG in a clinical setting. With a large sample size (n = 102), the study found a moderate correlation (correlation coefficient = 0.43) between isometric ankle plantarflexor strength measured with HHD and APG measured using 3DGA (Kahn & Williams, 2015). Despite the clinical utility of HHD, the low association results between HHD measures of isometric muscle strength and joint power generation led the authors to suggest that strength (as measured by HHD) may not accurately reflect ankle plantarflexor power generation during the gait cycle in people with traumatic brain injury (Kahn & Williams, 2015). However, the study by Kahn and Williams (2015) did not normalise the isometric strength measures to body mass, which is an important step in the analysis of strength data to allow for interpretation of and comparison between scores from different participants. As power generation values are normalised to body mass, the use of absolute strength scores is a limitation of the study by Kahn and Williams (2015). In addition, the study did not assess the reliability of the strength assessor, which may have resulted in measurement error of the HHD between the participants.

Another study on people with spastic bilateral cerebral palsy also examined the associations between isometric muscle strength measured with HHD and joint power generation during gait (Dallmeijer et al., 2011). This study examined peak joint power generation at the hip, knee and ankle during gait and examined the associations with isometric hip, knee and ankle strength (Dallmeijer et al., 2011). The results revealed the only significant associations (that

were above weak values) were at the ankle with significant moderate correlations between isometric ankle plantarflexor strength and peak APG during gait (correlation coefficient = 0.41 and 0.57 for the right and left leg respectively) (Dallmeijer et al., 2011). These correlations are similar to those reported by Kahn and Williams (2015) in traumatic brain injury of 0.43. No significant correlations were found between isometric knee or hip strength and peak knee or hip power generation during gait (Dallmeijer et al., 2011). Similar to the previous study by Kahn and Williams (2015), the study by Dallmeijer et al. (2011) also did not report the reliability of the strength assessor.

Despite the two previous studies in other neurological populations, research examining the relationship between ankle plantarflexor muscle strength and APG during gait has not been previously tested in the stroke population and may provide different results to those observed in people with traumatic brain injury or bilateral spastic cerebral palsy. By assessing the reliability of the strength assessor, the potential for erroneous results may be reduced in comparison with the previous studies (Dallmeijer et al., 2011; Kahn & Williams, 2015). Additionally, the association between the strength of other muscle groups and joint power generation during gait has not been examined following stroke (e.g. association between isometric hip flexor strength and hip flexor power generation during gait).

It may also be pertinent to examine other clinically feasible measures besides muscle strength that are predictive of gait velocity and joint power generation throughout the gait cycle. The following section will examine a different component of muscle function, muscle power, which may provide a stronger relationship with both gait velocity and joint power generation during gait following stroke.

2.4 Muscle power and gait

Muscle power refers to the rapid contraction of muscles (Bean et al., 2002). In the stroke population it has been reported that there is decreased ability to produce force quickly (muscle power) in both the paretic upper and lower limbs, compared with the non-paretic limb and with healthy controls (Canning et al., 1999; Fimland et al., 2011; Gerrits et al., 2009; Knight et al., 2014; Pohl et al., 2002; Stavric & McNair, 2012). Initial research in the stroke population has shown that measures of muscle power can provide additional value to measures of muscle strength for the relationship with gait velocity (Pohl et al., 2002). Promising results have also been demonstrated in studies of the elderly, with muscle power shown to be more strongly associated with self-reported function, incidence of falls and physical performance than muscle strength (Bean et al., 2002; Fleming, Wilson, & Pendergast, 1991; Foldvari et al., 2000; Skelton et al., 2002). The assessment of muscle power can be performed through various methods that will be outlined in the following section.

2.4.1 Assessment of muscle power

Muscle power can be calculated using different methods: by multiplying force by velocity ($Power = F.v$), by dividing work by time ($Power = W/\Delta t$) or by dividing torque, which is force multiplied by the lever arm, by time ($Power = F.d/\Delta t$). Additionally, rotational power is calculated by multiplying torque by angular velocity ($Power = \tau.\omega$). No matter the calculations used, the point of difference of muscle power, compared with strength, is the speed of movement. This is an important consideration when reviewing the literature on muscle power.

Muscle power can be measured using many different devices. Devices capable of assessing dynamic muscle power include linear position transducers (Alemany et al., 2005; Garnacho-Castaño, López-Lastra, & Maté-Muñoz, 2015; Stavric & McNair, 2012; Villadsen, Roos, Overgaard, & Holsgaard-Larsen, 2012), power rigs (Bassey et al., 1992; Dawes et al., 2005; Saunders, Greig, Young, & Mead, 2008; Skelton et al., 2002; Villadsen et al., 2012), and force plates (Davies, White, & Young, 1983; McMaster et al., 2014; Stavric & McNair, 2012). However, the cost, accessibility and time demands of such assessments may limit their use in clinical settings and therefore, will not be addressed in this thesis. Moreover, the testing procedures often involve bulky and difficult equipment and require exercises or movements with high physical demands which may not be suitable in the stroke population.

A common measure used during muscle assessment is the rate of force development (RFD), which can be assessed from a range of different devices and provides an indication of 'explosive muscle strength' or 'isometric muscle power'. The terminology used in research is either RFD or the rate of torque development (RTD). The RFD or RTD can be calculated by determining the change in force (or torque) over change in time during an isometric contraction ($Power = N.m/\Delta t$) (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002; Caserotti, Aagaard, Buttrup Larsen, & Puggaard, 2008). The measure of RFD relates to the speed at which force (or torque) can be produced and can be considered a measure of muscle power, despite the isometric nature of testing. The method for assessment of RFD is identical to that of muscle strength, whereby an isometric MVC occurs, although the initial rise in force is examined rather than just the peak amount of force produced (see Figure 2.3). For the remainder of the current section, the term RFD will be used when discussing both RFD and RTD.

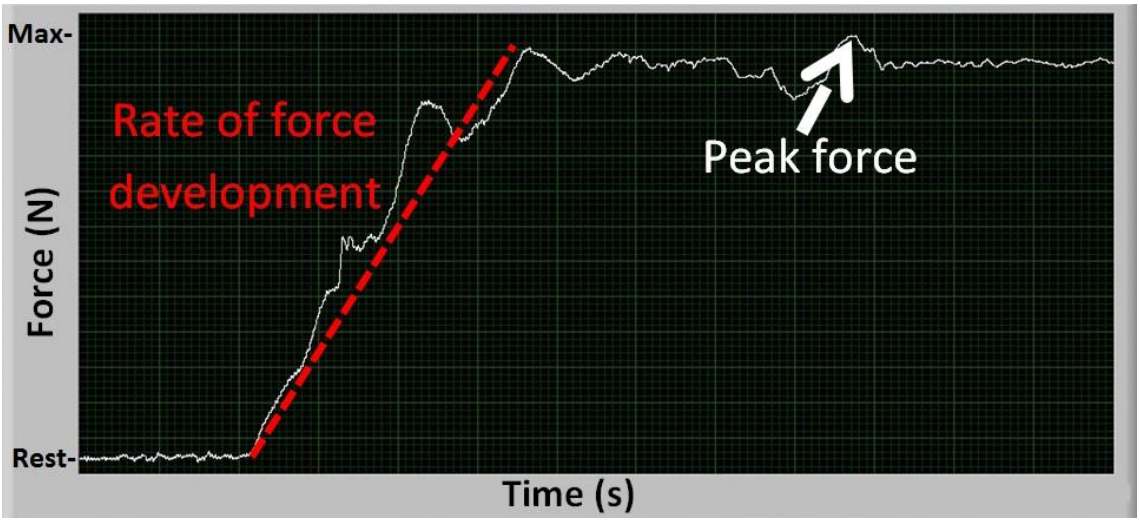

Figure 2.3. Raw force trace for the assessment of isometric muscle power (rate of force development) from a maximal voluntary contraction measured by dynamometry. The arrow shows the point of peak force used for strength assessment and the dashed line indicates the initial rise in force from which rate of force development is calculated. Rate of torque development is assessed in the same manner, with torque (Nm) being displayed on the y-axis instead of force (N).

Currently there are varying methods utilised to calculate RFD. Commonly used methods involve calculating the change in force over the change in time with discrete time intervals from the onset of muscle contraction to 30, 50 or 100ms (Aagaard et al., 2002; Andersen & Aagaard, 2006; Suetta et al., 2004). The onset of contraction has been defined in different ways including when the force reading exceeds a set threshold of either absolute values (e.g. 5N) or percentages of MVC (e.g. 5% of peak force) (Aagaard et al., 2002; Andersen & Aagaard, 2006; Andersen, Andersen, Zebis, & Aagaard, 2010; Blazevich, Horne, Cannavan, Coleman, & Aagaard, 2008; Pijnappels, van der Burg, Reeves, & van Dieën, 2008), limiting the ability to compare results between studies which utilise varying methods. Previous work has commented on the arbitrary nature of determining onset of contraction for calculation of RFD (Pua, Wrigley, Collins, Cowan, & Bennell, 2009) and has suggested calculation of peak RFD across the trial. Such methods of calculating peak RFD involve examining successive time intervals (e.g. 5ms or 30ms) during the initial rise in force to determine the

peak RFD across the trial (Bemben, Massey, Bemben, Misner, & Boileau, 1991; Korhonen et al., 2006; Kyröläinen et al., 2005; Pua et al., 2009). Other methods include examining the RFD between percentages of the peak force (e.g. between 30 and 60% of peak force) (Sleivert & Wenger, 1994). There is currently no consensus as to which measure of RFD should be used for the assessment of isometric muscle power.

The measure of RFD has been used numerous times in clinical populations (e.g. stroke and cerebral palsy) (Aagaard, Suetta, Caserotti, Magnusson, & Kjær, 2010; Fimland et al., 2011; Gerrits et al., 2009; Izquierdo, Aguado, Gonzalez, López, & Häkkinen, 1999; Maffiuletti, Bizzini, Widler, & Munzinger, 2010; Moreau, Falvo, & Damiano, 2012; Pohl et al., 2002) and may have important functional significance in quick and forceful muscle contractions, such as those that occur during gait (Aagaard et al., 2002). Previous research has indicated that RFD declines with age, even more so than muscle strength (Aagaard et al., 2010; Izquierdo et al., 1999). In people following total knee arthroplasty, RFD has shown to be significantly reduced six months following surgery and is more strongly correlated with assessments of subjective knee function than measures of muscle strength (Maffiuletti et al., 2010). Additional regression analysis in the total knee arthroplasty population demonstrates that RFD significantly improves the prediction of physical function compared with muscle strength (Winters, Christiansen, & Stevens-Lapsley, 2014). Early after anterior cruciate ligament reconstruction, RFD, not strength, is associated with self-reported knee function (Hsieh, Indelicato, Moser, Vandenborne, & Chmielewski, 2015). Similar results have been found in children with cerebral palsy, with RFD significantly lower when compared to typically developing children and RFD demonstrating stronger correlations compared to muscle strength with self-reported measures of physical function and disability (Moreau et al., 2012). Despite the potential importance of RFD, current methods to assess RFD require

expensive laboratory-based equipment (e.g. fixed dynamometry) which has precluded the use of the measure of isometric muscle power in clinical settings for routine assessment.

Recent iterations of HHDs have allowed clinicians and researchers to export the raw force trace for further analysis. This advancement may allow for the calculation of RFD from isometric strength testing using HHD. The additional outcome measure of RFD involves a further step in data analysis, with no change from the strength assessment protocol for data collection. To date, it appears there has been no research examining the use of HHD for the assessment of RFD in any population. There is a large amount of research examining the use of HHD for strength assessment within the stroke population, and documenting the relationship between strength and function (Bohannon, 1989b; Bohannon & Walsh, 1991; Dorsch et al., 2012; Kligyte, Lundy-Ekman, & Medeiros, 2003; Lin et al., 2006; Ng, 2011). The addition of measures of RFD may rapidly increase the current understanding of how muscle strength and power relates with gait function following stroke.

Recently it has been suggested that measures of muscle power need to be investigated as muscle power may be more strongly correlated with gait than measures of muscle strength (Dorsch et al., 2012). This is a logical hypothesis, especially when considering the role that joint power generation during gait (another measure similar to muscle power that is also dependent on speed) has in determining gait velocity after stroke (Jonkers et al., 2009; Kim & Eng, 2004). When considering the short time period of an entire gait cycle following stroke (even on the paretic side, gait cycle time has been reported to be between 1.28 to 1.50 seconds) (Dettmann et al., 1987; Kim & Eng, 2003b; Lin et al., 2006; Von Schroeder et al., 1995) and that each muscle group only activates for discrete periods within this timeframe, the ability for muscle groups to contract quickly may be more important for gait than just the peak amount of force that a muscle group can produce. However, there is currently a

paucity of research examining the relationships between isometric muscle power and gait following stroke.

2.4.2 Associations between isometric muscle power and gait velocity

In an attempt to further the understanding of muscle power following stroke the focus of this thesis will be on clinically feasible measures of muscle power such as isometric analysis of RFD from HHD. The ability of a muscle group to *rapidly* produce force may be more important for gait than the ability of that muscle group to produce a *large amount* of force. Previous studies in the stroke population have examined the relationship between gait velocity and other dynamic measures of muscle power from isokinetic dynamometry (Bohannon, 1992; LeBrasseur, Sayers, Ouellette, & Fielding, 2006) and power rigs (Dawes et al., 2005; Saunders et al., 2008) with mixed results found depending on the study design and equipment used. These devices lack clinical feasibility and it may be more pertinent to examine measures of muscle power that are able to be collected quickly and easily by clinicians, such as isometric muscle power.

Compared with muscle strength, there is limited research examining the associations between measures of isometric muscle power and gait velocity, and very little that examines the difference in correlation values between measures of strength and power following stroke. Two previous studies with small sample sizes (n = 14 and 16 respectively) have examined correlations between isometric measures of muscle power and gait velocity following stroke (Bohannon & Walsh, 1992; Nadeau et al., 1997). The small sample sizes included indicates that interpretation of the results should be done with caution, as the studies may be underpowered and have a limited spread of results which can affect the correlation values. Muscle power of the knee extensors was measured in the first study (Bohannon & Walsh, 1992) by measuring the time taken to reach peak force. This study

found a significant strong association between peak force (i.e. muscle strength) and gait velocity (correlation coefficient = 0.67), whereas time to peak force had a very weak association (correlation coefficient = -0.07) (Bohannon & Walsh, 1992). However, time to peak force is a poor measure of muscle power. During isometric testing, peak force could occur anywhere in the plateau in force (when the participant is contracting maximally) and as such peak force may occur towards the end of the recorded trial, thus resulting in the calculation of 'poor muscle power' (see Figure 2.4). The study by Nadeau et al. (1997) recorded maximal rate of tension development (i.e. RFD) during an isometric contraction as their measure of muscle power. A similar correlation was found with maximal gait velocity between ankle plantarflexor strength and power measures (correlation coefficients = 0.29 and 0.31 for strength and RFD respectively) (Nadeau et al., 1997). However, the study by Nadeau et al. (1997) included a small sample size (n = 16) and there was little information provided on the type of analysis used to calculate muscle power (Nadeau et al., 1997). These two studies highlight the need for further research to examine RFD following stroke and how this measure relates to gait function.

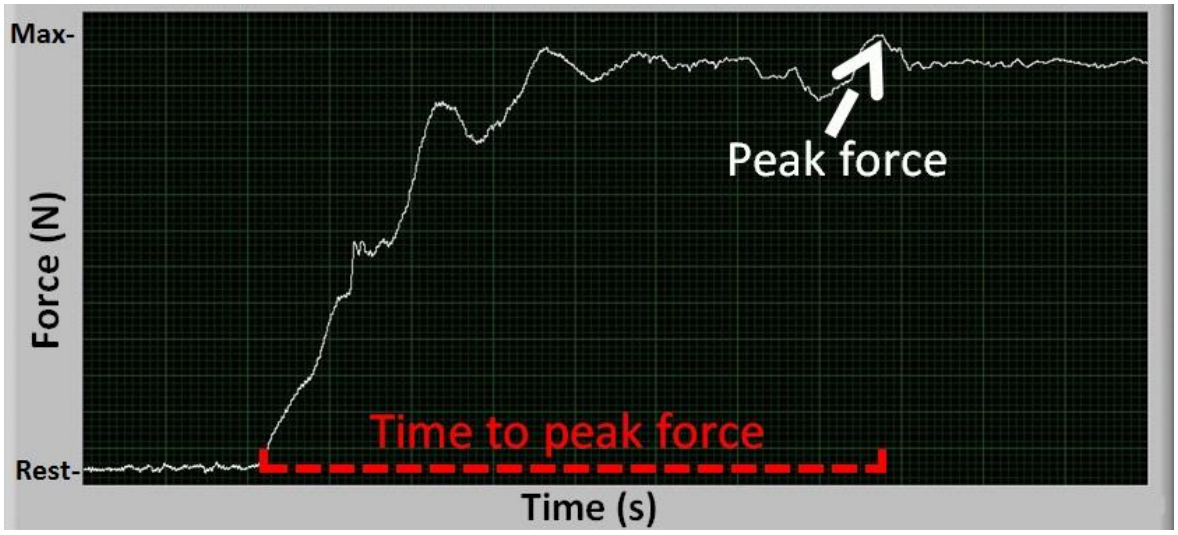

Figure 2.4. Assessment of time to peak force from a maximal voluntary contraction. The arrow shows the point of peak force used for strength assessment and the dashed line indicates the time to peak force measure. For this particular force trace, the peak force occurs towards the end of the trial indicting poor muscle power if the time to peak force measure is used.

Another study by Pohl et al. (2002) employed a much larger sample size (n = 83) to examine the relationship between isometric muscle power of the knee extensors and gait velocity following stroke (Pohl et al., 2002). A detailed analysis was provided that compares the relationship of strength and power with gait velocity. This study found that isometric muscle power explained more of the variance in gait velocity compared to muscle strength. After creating a regression model that included both isometric strength and power (plus covariates of age and gender), removal of strength from the model did not reduce the R^2, however removal of isometric power significantly reduced the R^2 calculated (Pohl et al., 2002). This indicates that in this sample muscle power had a stronger relationship with gait velocity than muscle strength following stroke. However, the regression model, which included age, gender, knee extensor peak force and knee extensor RTD, explained only 12% of the variance in gait velocity (Pohl et al., 2002), suggesting that there may be other factors that impact upon gait velocity after stroke. The variance in gait velocity may be better explained

through the assessment of the ankle or hip muscle groups, which are important for forward progression.

The measure of muscle power used in the study by Pohl et al. (2002) was RTD (i.e. RFD) of the knee extensors, as defined by placing a linear fit over the initial rise in torque of an isometric contraction. The use of a linear fit may not truly represent the RFD occurring across the entire trial and therefore may be a poor measure of RFD. Another limitation of the study by Pohl et al. (2002) was the participants were allowed to walk with their usual assistive devices or orthoses. Such devices can alter the contributions a muscle makes by changing the strength requirements of gait (Dorsch et al., 2012). Even the use of simple assistive devices such as walking canes can influence spatiotemporal, kinematic and kinetic variables (including joint power generation) during gait (Kuan, Tsou, & Su, 1999; Polese et al., 2012), thus potentially affecting the correlations between strength or power and gait velocity. Although the study by Pohl et al. (2002) used isometric knee extensor strength and power to predict gait velocity, it demonstrates that muscle power may play a stronger role in determining gait velocity following stroke compared with the traditional measure of muscle strength.

Despite the regression model in the study by Pohl et al. (2002) only predicting a small amount of variance in gait velocity, the analysis of the association between gait velocity and muscle power deserves further attention, especially in other lower limb muscle groups. Additionally, the study used an expensive laboratory-based dynamometer which lacks applicability in a clinical setting and allowed participants to use their usual assistive devices during gait assessment. The use of clinically feasible measures of muscle power, such as HHD, may provide clinicians with an informative assessment of their patients' physical function.

2.4.3 Associations between isometric muscle power and joint power generation during gait

Limited research exists examining the relationship between clinically feasible measures of muscle function (i.e. muscle strength and/or power) and joint power generation during gait following stroke. Given the moderate correlations between isometric ankle plantarflexor strength and peak APG during gait for people following traumatic brain injury and bilateral spastic cerebral palsy (Dallmeijer et al., 2011; Kahn & Williams, 2015), muscle strength may not have a large association with power generation in the stroke population. However, further investigation is required to determine the associations between muscle function, especially muscle power, and joint power generation following stroke.

One study in 26 persons with knee osteoarthritis examined the relationship of measures of isometric strength and power (RFD) of the knee extensors with joint power generation of the knee during gait (Winters & Rudolph, 2014). A hierarchical regression was used to determine if isometric strength or peak RFD could predict power generation during gait. For power generation of the knee during self-selected walking speeds, peak RFD significantly accounted for 23.1% of the variance of power generation, whereas isometric knee strength did not significantly contribute to the prediction of knee joint power generation during gait (Winters & Rudolph, 2014). This result supports the study's hypothesis that isometric strength is not the only measure of muscle function that relates to biomechanical measures of gait (Winters & Rudolph, 2014). It is important to note that this study also found the opposite when examining knee joint power generation during fast paced gait, with RFD not significantly predicting power generation during fast gait and instead isometric strength significantly predicting 49% of the variance in knee joint power generation (Winters & Rudolph, 2014). This result indicates further research is needed to determine how measures

of strength and power interact and impact upon gait function. The study by Winters and Rudolph (2014) examined knee strength and power (as their participants had knee osteoarthritis), however the ankle and hip joints produce the majority of power generation during gait (Williams & Schache, 2016) and therefore it may be more important to examine the relationship between these muscle group and joint power generation during gait (e.g. hip RFD and hip power generation during gait). No previous research has examined the association between isometric muscle power and joint power generation during gait following stroke.

2.5 Conclusion

The restoration of walking is accepted as a key goal following stroke. Gait velocity is a commonly measured variable and a well-known indicator of overall gait performance in stroke. Another important measure of gait function following stroke is joint power generation throughout the gait cycle. Identification of key variables that relate to and affect gait is important to understand the mechanisms of the gait impairments and to guide future intervention strategies for people following stroke. Many factors have been suggested to contribute to reduced walking ability following stroke, although it has been proposed that lower limb muscle weakness is one of the main contributors to physical limitations.

A commonly used device to measure isometric lower limb muscle strength is HHD, which has been reported to be the most appropriate and convenient method of assessing muscle strength in a clinical setting. Equivocal correlation results have been found between lower limb isometric strength and gait velocity following stroke depending on the muscle group assessed and the sample size utilised. Additionally, examination of the relationship between muscle strength and joint power generation during gait has not previously occurred in the stroke population.

The ability for muscle groups to contract quickly may be more important for gait than reporting the peak amount of force that a muscle group can produce. Hand-held dynamometry has not been used previously for the assessment of isometric muscle power. Understanding the association between isometric muscle power and gait may provide further insight into gait impairments and guide future rehabilitation strategies following stroke.

CHAPTER THREE: ASSOCIATIONS BETWEEN ISOMETRIC STRENGTH AND GAIT VELOCITY FOLLOWING STROKE: A SYSTEMATIC REVIEW (STUDY ONE)

3.1 Preamble

Due to the large amount of research identified in Section 2.3.2, a systematic review was conducted to examine the associations between lower limb isometric muscle strength and gait velocity following stroke. The systematic review will provide a strong research background to identify the strengths and weaknesses of the previous literature, which will inform the design of the subsequent studies. This chapter presents the findings of a peer-reviewed manuscript, which has been adapted with permission for this thesis. The manuscript has been published in *Brain Injury* (Mentiplay et al., 2015a) and the full text is provided in Appendix F. As this study had already been published, the systematic search was performed prior to publication with the search not updated prior to submission of this thesis.

3.2 Introduction

Stroke is a leading cause of disability worldwide (Adamson et al., 2004; Feigin et al., 2014) that may result in a range of physical limitations or impairments. Whilst there are many methods that can be used for the assessment of physical impairment or function, such as the Timed Up and Go (Podsiadlo & Richardson, 1991) or the Six Minute Walk Test (Butland, Pang, Gross, Woodcock, & Geddes, 1982), the measure of gait velocity has shown to be

predictive of length of hospital stay, functional outcome and community ambulation (Lord et al., 2004; Perry et al., 1995; Salbach et al., 2001) and has been previously associated with physical activity levels following stroke (Mudge & Stott, 2009). Adding to the clinical importance of the measure of gait velocity, a key factor of rehabilitation following stroke is to regain the ability to independently walk at a speed that allows for community ambulation (e.g. being able to cross busy pedestrian crossings in a timely manner) and as such, improving walking speed is a major goal of rehabilitation (Kwakkel & Kollen, 2013).

Examining the associations between gait velocity and other aspects of function may provide insight into the factors that impact upon walking speed following stroke and therefore could assist clinicians to better understand how to target improvements in gait velocity and potentially develop appropriate intervention strategies. A lack of muscle strength has been proposed as one of the primary factors associated with physical limitations and reduced gait velocity after stroke (Ada et al., 2006; Bohannon, 1989b; Canning et al., 2004; Taylor-Piliae, Latt, Hepworth, & Coull, 2012). Many previous studies have examined the association between gait velocity and muscle strength, although large discrepancies exist between studies when analysing this relationship.

Therefore, the aim of Study One was to systematically review the current literature investigating the associations between isometric muscle strength of individual lower limb muscle groups and gait velocity following stroke. A systematic review design was utilised to enable the rigorous collection and synthesis of the existing results to guide the design of subsequent studies of this thesis. It was hypothesised that the strength of those muscle groups responsible for forward progression, namely the ankle plantarflexors, would demonstrate strong correlations with gait velocity.

3.3 Methods

3.3.1 Search strategy

An electronic search was conducted using six online databases from inception to August 2013 (Scopus, Medline, Cumulative Index of Nursing and Allied Health Literature, Web of Science, Embase and PubMed). These databases were chosen because they covered a range of disciplines such as allied health, medical science, nursing and health sciences. Key search terms and relevant synonyms were consistent across all databases and relevant medical subject headings (MeSH) were used if possible. Example search strategies for a database with MeSH (Medline) and without MeSH (Web of Science) terms are provided in Table 3.1. Targeted searching of the reference lists of included articles and three relevant journals (*Archives of Physical Medicine and Rehabilitation, Gait & Posture*, and *Stroke*, from 2008 onwards) was also performed to identify potential articles that were missed from the systematic database search.

Table 3.1. Search strategy for databases with and without Medical Subject Headings

	Medline
#1	(MH "Cerebral Hemorrhage") OR (MH "Brain Infarction") OR (MH "Cerebral Infarction") OR (MH "Intracranial Hemorrhages") OR (MH "Brain Ischemia") OR (MH "Stroke")
#2	(MH "Muscle Strength") OR (MH "Muscle Strength Dynamometer") OR (MH "Muscle Contraction") OR (MH "Isometric Contraction")
#3	(MH "Gait") OR (MH "Locomotion") OR (MH "Walking")
#4	AB (stroke OR (cerebrovascular accident) OR CVA OR (cerebral infarct*) OR (brain infarct*) OR (intracranial haemorr*) OR (intra-cranial haemorr*) OR (intracranial hemorr*) OR (intra-cranial hemorr*) OR (cerebral haemorr*) OR (cerebral hemorr*) OR (cortical haemorr*) OR (cortical hemorr*) OR (cortical ischaem*) OR (cortical ischem*) OR (cerebral ischaem*) OR (cerebral ischem*) OR (brain ischaem*) OR (brain ischem*)) OR TI (stroke OR (cerebrovascular accident) OR CVA OR (cerebral infarct*) OR (brain infarct*) OR (intracranial haemorr*) OR (intra-cranial haemorr*) OR (intracranial hemorr*) OR (intra-cranial hemorr*) OR (cerebral haemorr*) OR (cerebral hemorr*) OR (cortical haemorr*) OR (cortical hemorr*) OR (cortical ischaem*) OR (cortical ischem*) OR (cerebral ischaem*) OR (cerebral ischem*) OR (brain ischaem*) OR (brain ischem*))
#5	AB (strength* OR (muscle strength*) OR (muscle contract*) OR power OR (muscle force) OR MVC OR (max* volunt* contract*) OR dynamo* OR isometric* OR isokinetic*) OR TI (strength* OR (muscle strength*) OR (muscle contract*) OR power OR (muscle force) OR MVC OR (max* volunt* contract*) OR dynamo* OR isometric* OR isokinetic*)
#6	AB (gait OR mobility OR walk* OR ambulat* OR locomot*) OR TI (gait OR mobility OR walk* OR ambulat* OR locomot*)
#7	#1 OR #4
#8	#2 OR #5
#9	#3 OR #6
#10	#8 AND #9
#11	#7 AND #10 (Limiters – English Language; Human)
	Web of Science
#1	Topic = (stroke OR (cerebrovascular accident) OR CVA OR (cerebral infarct*) OR (brain infarct*) OR (intracranial haemorr*) OR (intra-cranial haemorr*) OR (intracranial hemorr*) OR (intra-cranial hemorr*) OR (cerebral haemorr*) OR (cerebral hemorr*) OR (cortical haemorr*) OR (cortical hemorr*) OR (cortical ischaem*) OR (cortical ischem*) OR (cerebral ischaem*) OR (cerebral ischem*) OR (brain ischaem*) OR (brain ischem*)) OR Title = (stroke OR (cerebrovascular accident) OR CVA OR (cerebral infarct*) OR (brain infarct*) OR (intracranial haemorr*) OR (intra-cranial haemorr*) OR (intracranial hemorr*) OR (intra-cranial hemorr*) OR (cerebral haemorr*) OR (cerebral hemorr*) OR (cortical haemorr*) OR (cortical hemorr*) OR (cortical ischaem*) OR (cortical ischem*) OR (cerebral ischaem*) OR (cerebral ischem*) OR (brain ischaem*) OR (brain ischem*))
#2	Topic = (strength* OR (muscle strength*) OR (muscle contract*) OR power OR (muscle force) OR MVC OR (max* volunt* contract*) OR dynamo* OR isometric* OR isokinetic*) OR Title = (strength* OR (muscle strength*) OR (muscle contract*) OR power OR (muscle force) OR MVC OR (max* volunt* contract*) OR dynamo* OR isometric* OR isokinetic*)
#3	Topic = (gait OR mobility OR walk* OR ambulat* OR locomot*) OR Title = (gait OR mobility OR walk* OR ambulat* OR locomot*)
#4	#3 AND #2
#5	#4 AND #1
#6	#4 AND #1 (Refined by: Languages = (English) AND [excluding] Document Types = (Review OR Book Chapter OR Letter OR Editorial Material OR Meeting Abstract OR Note))

Note: MH = Medical Subject Heading; AB = abstract; TI = title. Table adapted with permission from Mentiplay et al. (2015a).

3.3.2 Eligibility criteria

The eligibility criteria for this review are provided in Table 3.2. Only original, full text research articles that were published in English were examined. Grey literature (e.g. book chapters) and conference abstracts were excluded from review due to the limited rigorous peer review process. Review articles were also excluded as they do not provide original research. All research designs were included, except for case studies as they possess a high potential for bias and it can be difficult to generalise the results to a larger population. Articles were required to include a bivariate correlation between gait velocity and at least one measure of strength from the muscles surrounding a single joint of the lower limb. Studies which only reported correlations of the change between pre and post intervention measures of gait or strength were excluded. Studies that only reported regression results were also excluded, as comparing regression values across studies is problematic due to differing statistical methods and covariates used in the research.

For the current review, strength measures were required to be an isometric test of an individual lower limb muscle group, regardless of the strength assessment device used. Measurement of isometric strength has demonstrated good consistency between clinical-based (i.e. HHD) and laboratory-based fixed dynamometry devices (Stark et al., 2011) and therefore both dynamometers were included in this review. Dynamic or isokinetic strength assessments were excluded as there is currently a lack of availability of devices required for such testing in clinical settings due to the expense and cumbersome nature of assessment (Moriello & Mayo, 2006). Composite scores of lower limb strength were excluded as no information is provided on the strength of individual muscle groups. Strength of the paretic limb following stroke was the focus of this thesis, however correlations involving the strength of the non-paretic limb are also provided in the appendices (Appendix A).

The measure of gait velocity was required to be assessed over a short linear distance, regardless of the device used to measure time (e.g. stopwatch or 3DGA), as these methods are highly correlated (Clark, Paterson, Ritchie, Blundell, & Bryant, 2011). Additionally, stopwatch measurements of gait velocity have demonstrated high inter-rater and test-retest reliability in neurological populations (Flansbjer et al., 2005; Holden, Gill, Magliozzi, Nathan, & Piehl-Baker, 1984). Functional assessment such as the Timed Up and Go (Podsiadlo & Richardson, 1991) and the Six Minute Walk Test (Butland et al., 1982), were excluded as they are indicative of other aspects of functional performance, for example sit to stand ability (Podsiadlo & Richardson, 1991) and endurance (Harada, Chiu, & Stewart, 1999) respectively.

Table 3.2. Selection criteria for studies to be included in the systematic review

Include	Exclude
Human adults over 18 years of age following stroke	Measures of functional performance (e.g. Timed Up and Go)
Measure of gait velocity performed over a short linear distance without rest	Dynamic, isokinetic or composite strength assessment
Measure of isometric strength of individual lower limb muscle groups	Regression analysis without bivariate correlation values being reported
Bivariate correlation between gait velocity and isometric strength	Correlations of change score pre and post intervention
	Grey literature, conference abstracts or review articles
	Case studies
	Published in language other than English

Note: Table adapted with permission from Mentiplay et al. (2015a).

3.3.3 Article selection

The title and abstract of each article in the initial yield was screened for eligibility by one reviewer (thesis author BFM) and all non-stroke related articles were removed. The selection criteria were then independently applied to the remaining articles by two reviewers (thesis author BFM and publication co-author GT). The final included articles were agreed upon by both reviewers, with differences resolved through discussion and mutual agreement. If consensus could not be achieved, a third independent reviewer (thesis co-supervisor BA) was consulted.

3.3.4 Data extraction and quality assessment

Data were independently extracted using a pre-determined and customised data extraction form by two reviewers (thesis author BFM and publication co-author GT). Extracted data included participant characteristics, gait and strength outcome measures used and correlation values. Correlation results were interpreted based on the suggestions of Evans (1996), with values taken as very weak (< 0.20), weak (0.20 to 0.39), moderate (0.40 to 0.59), strong (0.60 to 0.79) and very strong (≥ 0.80).

There is currently a lack of consensus on the most appropriate tool for the measurement of methodological quality in observational research (Sanderson, Tatt, & Higgins, 2007; Shamliyan, Kane, & Dickinson, 2010). Previously published quality assessments tools have been designed for the assessment of specific research designs (e.g. randomised controlled trials) and would not necessarily meet the more heterogeneous design requirements of this review. One previous systematic review of correlational results used a customised tool specifically designed to assess the methodological quality of correlation studies in those with Parkinson's disease (Tan, Danoudis, McGinley, & Morris, 2012). The tool developed by

Tan et al. (2012) was based on relevant criteria from two previously published quality assessment tools (Downs & Black, 1998; Law et al., 1998). Although the psychometric properties of this tool are yet to be determined, the design of this quality assessment tool made it the most appropriate for use in the current review. The original tool developed by Tan et al. (2012) was created for use in persons with Parkinson's disease and was adapted for use to make it relevant for studies of people following stroke (e.g. question four was changed to include pertinent stroke details such as time since stroke). For each question, an arbitrary score of 0 indicated low quality, 0.5 indicated medium quality and a score of 1 indicated high quality methodological reporting. This tool, which had a maximum score of 20, can be seen in Table 3.3. Guidelines for this tool have yet to be established regarding what overall score can be considered high or acceptable methodological quality. During the current review, the included articles were compared based on quality scores and the different methodological components identified as being important for correlation studies.

Methodological quality assessment was performed independently by two reviewers (thesis author BFM and publication co-author GT). Any discrepancies for either data extraction or quality assessment were resolved through discussion and mutual consensus. If such consensus could not be reached, a third independent reviewer was consulted (thesis co-supervisor BA).

Table 3.3. Methodological quality assessment tool

Reporting	
1. Were the research aims / questions / hypotheses stated clearly?	0: Unclear as to the aims of the study 0.5: Only aims with no hypotheses 1: Everything clearly stated
2. Were the inclusion and exclusion criteria clearly described?	0: Unclear as to the criteria used in the study 0.5: Limited description 1: Clear as to the criteria for inclusion/exclusion
3. Were gait and strength measures clearly described?	0: Neither measure clearly described 0.5: Only one measure described clearly 1: Both clearly described
4. Were participant characteristics detailed adequately? (Sample size, Age, Time since stroke, Type of stroke, Side of hemiparesis)	One point per sub category (1: it was reported, 0: it was not reported). Add together and divide by the number of sub categories (5 in this case).
5. Are the main findings of the study clearly described?	0: Main findings unclear 0.5: Limited description of the main findings 1: Clearly described
6. Does the study provide estimates of the random variability in the data for the strength and gait measures?	0: No measures of variability provided for both 0.5: Only SD or only range provided for one test 1: Provides a measure of the total variability (SD and range) for both strength and gait
7. Was the r-value of each individual correlation reported?	0: Not reported for each individual correlation 0.5: Only reported for a few, not all 1: Reported for each individual correlation
8. Was the significance (*p*-value) reported for each correlation?	0: *p*-value not reported for each correlation 0.5: *p*-value reported as * ($p < 0.05$) 1: *p*-value reported for each correlation
9. Were the key results summarised with reference to study objectives?	0: Results not summarised and no reference to study objectives 0.5: Somewhat summarised 1: Results summarised with reference to study objectives
10. Were clinical implications of the research stated?	0: No clinical implications stated 0.5: Clinical implications unclear 1: Clinical implications stated
11. Were the limitations of the study discussed?	0: No limitations reported 0.5: Limitations briefly discussed, missing obvious limitations 1: Limitations clearly discussed

External Validity	
12. Were those subjects who were prepared to participate representative of the population from which they were recruited?	0: No (e.g. only people who responded to ads or flyers) 1: Yes 0: Not documented or unable to determine
Internal Validity	
13. Were the main statistical tests used to assess the main outcomes appropriate?	0: Statistics used are inappropriate 1: Appropriate statistics used for correlation (e.g. Pearson or Spearman)
14. Was the reliability of the tool used to measure strength stated?	0: Not stated 1: Stated the reliability of the tool with references or tested in the study
15. Was the reliability of the assessor who measured strength stated?	0: Not tested 1: Assessed reliability of assessor and reported values (e.g. intraclass correlation coefficient)
16. Was information provided on the training and/or experience of the assessor?	0: No information provided 1: Gave information on the training and/or experience of the assessor
17. Were any efforts to address potential source of selection bias described?	0: Not mentioned 1: Mentioned attempts to reduce selection bias
18. Was there adequate adjustment for confounding in the gait analyses from which the main findings were drawn?	0: Allowed to use AFO or walking device during gait tests and results analysed with non-assisted participants 1: Nobody used AFO or walking device during gait tests OR allowed to use AFO then they were removed from analysis 0: Not documented or unable to determine
Power	
19. Was the sample size justified?	0: No sample size calculation performed 1: Sample size calculation for correlation performed
20. Was the sample size at 28 or above, which is needed to detect a moderate correlation (r-value of 0.50), powered at 80% with a two tailed significance level of 0.05?	0: Sample size was below 28 1: Sample size was 28 or above

Note: SD = standard deviation; AFO = ankle foot orthoses. Assessment tool modified from Tan et al. (2012). Table adapted with permission from Mentiplay et al. (2015a).

3.4 Results

The stages involved in the identification of suitable articles are presented in Figure 3.1. The initial yield, after removal of duplicates, was 2598 articles. Twenty articles were identified as meeting the selection criteria (Bohannon, 1986a, 1989a, 1991, 1992; Bohannon & Andrews, 1990; Bohannon & Walsh, 1992; Davies et al., 1996; Dorsch et al., 2012; Horstman et al., 2008; Kobayashi et al., 2011; Lam et al., 2010; Lin et al., 2006; Lin, 2005; Liu-Ambrose et al., 2007; Maeda et al., 2000; Nadeau et al., 1997; Nakamura et al., 1985; Nasciutti-Prudente et al., 2009; Ng & Hui-Chan, 2012; Severinsen et al., 2011), with one additional article included after targeted searching (Bohannon, 1989b). Seven of the articles were published by Bohannon and colleagues (Bohannon, 1986a, 1989a, 1989b, 1991, 1992; Bohannon & Andrews, 1990; Bohannon & Walsh, 1992). There were concerns that the studies by Bohannon and colleagues may have included the same (or similar) cohort of participants, therefore the primary author was contacted to provide clarification. Three studies involved unique samples (Bohannon, 1989b, 1991, 1992), whilst four articles had some degree of overlap in the sample (Bohannon, 1986a, 1989a; Bohannon & Andrews, 1990; Bohannon & Walsh, 1992). After contacting the author, the degree of overlap of the participants remained unclear. To prevent exclusion of important and new results, all seven articles by Bohannon and colleagues remained in the review process. Nevertheless, the four studies that included some overlap in participants (Bohannon, 1986a, 1989a; Bohannon & Andrews, 1990; Bohannon & Walsh, 1992) may provide similar results and should be compared cautiously with other studies.

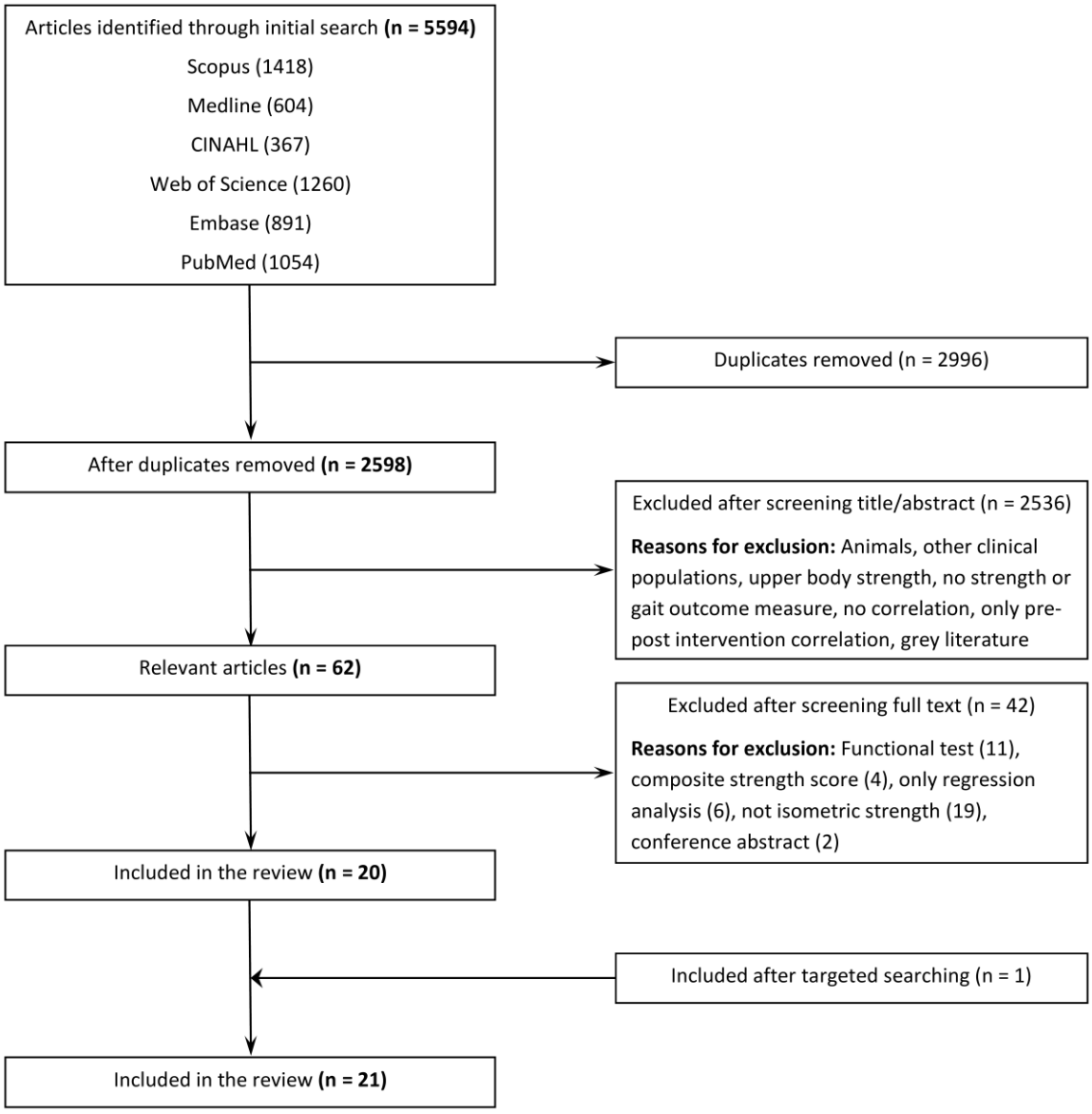

Figure 3.1. Flow diagram of article selection. Figure replicated with permission from Mentiplay et al. (2015a).

3.4.1 Participant characteristics

The characteristics of the participants included in each study are provided in Table 3.4. Eleven of the studies had 20 or fewer participants (Bohannon, 1986a, 1989a, 1992; Bohannon & Andrews, 1990; Bohannon & Walsh, 1992; Davies et al., 1996; Horstman et al., 2008; Kobayashi et al., 2011; Nadeau et al., 1997; Nakamura et al., 1985; Nasciutti-

Prudente et al., 2009) and seven studies had 40 or more participants (Dorsch et al., 2012; Lam et al., 2010; Lin et al., 2006; Liu-Ambrose et al., 2007; Maeda et al., 2000; Ng & Hui-Chan, 2012; Severinsen et al., 2011). All but one study (Nadeau et al., 1997) included participants with a mean age greater than 50 years (mean age across all studies = 47.9 to 70.6 years), 66% of participants were male and 51% had left-sided hemiparesis, with one study not reporting the side of hemiparesis (Nakamura et al., 1985). The time since stroke onset varied between and within studies, with the mean time ranging from 30.4 days up to 8.7 years (range = 4 days to 30.8 years). Only eight studies reported the type of stroke (Horstman et al., 2008; Kobayashi et al., 2011; Lam et al., 2010; Lin, 2005; Liu-Ambrose et al., 2007; Maeda et al., 2000; Nadeau et al., 1997; Severinsen et al., 2011).

Table 3.4. Participant characteristics for included studies

Article	Sample size (M/F)	Mean age ± SD (range) years	Mean time since stroke ± SD (range)	Side of hemiparesis (Left/Right)	Type of stroke	Gait test used	Gait speed assessed	Mean gait velocity ± SD (range), m/s	Assistive devices used (n)	Strength device used
Bohannon 1986a	20 (13/7)	60.8 ± 8.4	68 ± 46.6 (24 to 187) days	8/12	--	8m walk	Comfortable	0.51 ± 0.42 (0.09 to 1.67)	Walkers (8); quad-canes (6); single point canes (4); AFO (9)	HHD
Bohannon 1989a	12 (6/6)	64.4 ± 14.1 (33 to 78)	36.4 ± 10.7 (17 to 54) days	6/6	--	8m walk	Comfortable	0.26 ± 0.29 (0.05 to 1.02)	Ambulatory aids; orthoses	HHD
Bohannon 1989b	33 (15/18)	67.7 ± 11.1	30.4 ± 14.6 days	22/11	--	8m walk	Comfortable	0.16 ± 0.24	Rolling walkers; quad-canes; single point canes; AFO (total: 17)	HHD
Bohannon 1991	26 (13/13)	58.4 ± 11.7 (33 to 84)	69.5 ± 70.6 (14 to 320) days	12/14	--	8m walk	Comfortable	0.37 ± 0.34	?	HHD & Cybex
Bohannon 1992	20 (10/10)	63.7 ± 14.9 (28 to 82)	70 ± 109 (4 to 364) days	14/6	--	7m walk	Comfortable & Fast	--	--	Lido Active
Bohannon & Andrews 1990	17 (11/6)	59 ± 11.4 (33 to 84)	51 ± 41.8 (15 to 198) days	7/10	--	8m walk	Comfortable	0.34 ± 0.33	--	Cybex
Bohannon & Walsh 1992	14 (6/8)	68.1 ± 11 (48 to 83)	54.5 ± 93.3 (4 to 347) days	4/10	--	7m walk	Comfortable & Fast	--	Physical assistance for balance (2); single point or quad-canes (7); close supervision no physical assistance (5)	Lido Active
Davies et al 1996	12 (8/4)	59 ± 18 (24 to 75)	17 ± 12 (3 to 42) months	3/9	--	10m walk	Fast	0.61 ± 0.07	Walking aid (4)	Lido Active
Dorsch et al 2012	60 (42/18)	69 ± 11	(1 to 6) years	28/32	--	10m walk	Comfortable	0.75 ± 0.34 (0.09 to 1.41)	No assistive devices	HHD
Horstman et al 2008	14 (10/4)*	55.9 ± 10.4	109 ± 46 days	6/8	5 H / 9 I	10m walk	Comfortable	0.30 ± 0.17	--	LEXS
Kobayashi et al 2011	10 (10/0)	54.3 ± 8.4	8.7 ± 4.5 years	5/5	6 H / 4 I	5m walk	Fast	0.75 ± 0.19 (0.50 to 1.14)	?	HHD

Lam et al 2010	45 (27/18)	67.7 ± 11.3 (42 to 90)	< 6 months	25/20	7 H / 38 I	6m walk	Comfortable	0.49 ± 0.31 (0.06 to 1.20)	Canes (22); quad-canes (9); frame (5)	HHD
Lin et al 2006	68 (52/16)	61.69 ± 13.97 (31 to 82)	3.91 ± 5.87 (0.02 to 30.78) years	26/42	--	GAITRite	Comfortable	0.65 ± 0.32 (0.04 to 1.49)	No assistive devices	HHD
Lin 2005	21 (15/6)	65.2 ± 9.1	63.2 ± 55.5 months	13/8	9 H / 12 I	10m walk (3DGA)	Comfortable	--	Single point canes (1); quad-canes (9)	HHD
Liu-Ambrose et al 2007	63 (37/26)	65 ± 9 (52 to 87)	6 ± 5 (1 to 28) years	41/22	37 I	10m walk	Comfortable	0.8 ± 0.4 (0.1 to 2.1)	?	HHD
Maeda et al 2000	40 (21/19)	M: 69.6 ± 8.3 F: 70.6 ± 9.1	2.9-3.8 years	20/20	35 H / 5 I	10m walk	Fast	M: 0.69 ± 0.34 F:0.67 ± 0.41	?	HHD
Nadeau et al 1997	16 (12/4)	47.9 ± 15.6 (18 to 73)	43.9 ± 36.5 (2 to 105) months	4/12	5 H / 8 I 3 Unknown	9m walk	Comfortable & Fast	C: 0.76 ± 0.27 (0.41 to 1.50) Fast: 1.08 ± 0.33 (0.58 to 1.76)	Single point canes (4)	Biodex
Nakamura et al 1985	11 (10/1)	M: 53.8 (27 to 77) F: 50	4 (0.5 to 22.5) months	--	--	10m walk	Fast	0.92 ± 0.58 (0.16 to 1.92)	No assistive devices	Cybex
Nasciutti-Prudente et al 2009	12 (6/6)	70.57 ± 3.31 (65 to 75)	2.51 ± 2.82 (0.58 to 11) years	4/8	--	10m walk	Comfortable	0.65 ± 0.33 (0.15 to 1.31)	No assistive devices	HHD
Ng & Hui-Chan 2012	62 (51/11)	57.4 ± 7.8 (45 to 78)	5.2 ± 3.7 years	43/19	--	GAITRite	Comfortable	0.52 ± 0.26 (0.13 to 1.10)	Single point canes (62)	Load Cell
Severinsen et al 2011	48 (35/13)	68 ± 9 (50 to 80)	18 ± 6 (8 to 38) months	22/26	68 I	10m walk	Comfortable	0.84 ± 0.3	--	Biodex

Note: M = male; F = female; * = three participants could not perform gait test hence were not used for analysis; SD = standard deviation; H = haemorrhagic; I = infarct; m/s = metres per second; C = comfortable; AFO = ankle foot orthoses; -- = unable to determine (which assistive devices used); ? = not mentioned if assistive devices were allowed; HHD = hand-held dynamometry; Lido Active = Lido Active Rehabilitation System; LEXS = lower extremity system; Cybex = Cybex fixed dynamometer; Biodex = Biodex fixed dynamometer; 3DGA = three-dimensional gait analysis; GAITRite = GAITRite walkway system. Table adapted with permission from Mentiplay et al. (2015a).

3.4.2 Outcome measures

The outcome measures for gait velocity and isometric strength from each study are also shown in Table 3.4. Eighteen studies assessed gait velocity by using a stopwatch to time the participants over a short distance between 5 and 10 metres (Bohannon, 1986a, 1989a, 1989b, 1991, 1992; Bohannon & Andrews, 1990; Bohannon & Walsh, 1992; Davies et al., 1996; Dorsch et al., 2012; Horstman et al., 2008; Kobayashi et al., 2011; Lam et al., 2010; Liu-Ambrose et al., 2007; Maeda et al., 2000; Nadeau et al., 1997; Nakamura et al., 1985; Nasciutti-Prudente et al., 2009; Severinsen et al., 2011). Three studies used laboratory-type measures, being either GAITRite (a spatiotemporal gait analysis mat) (Lin et al., 2006; Ng & Hui-Chan, 2012) or a 3DGA system (Lin, 2005). Fourteen studies asked participants to walk at their comfortable speed (Bohannon, 1986a, 1989a, 1989b, 1991; Bohannon & Andrews, 1990; Dorsch et al., 2012; Horstman et al., 2008; Lam et al., 2010; Lin et al., 2006; Lin, 2005; Liu-Ambrose et al., 2007; Nasciutti-Prudente et al., 2009; Ng & Hui-Chan, 2012; Severinsen et al., 2011), four asked the participants to walk as fast as possible (Davies et al., 1996; Kobayashi et al., 2011; Maeda et al., 2000; Nakamura et al., 1985) and three performed trials at both speeds (Bohannon, 1992; Bohannon & Walsh, 1992; Nadeau et al., 1997). In terms of the reported gait velocity measure, the studies varied in their methods: seven articles used the average of three trials (Horstman et al., 2008; Kobayashi et al., 2011; Lin et al., 2006; Lin, 2005; Nasciutti-Prudente et al., 2009; Ng & Hui-Chan, 2012; Severinsen et al., 2011); four articles used one trial only (Bohannon, 1986a, 1992; Bohannon & Walsh, 1992; Liu-Ambrose et al., 2007); two articles used the average of two trials (Bohannon, 1991; Dorsch et al., 2012); two articles used the fastest of two trials (Lam et al., 2010; Maeda et al., 2000); one article collected and analysed two trials (Bohannon & Andrews, 1990); in four articles the method was unable to be determined (Bohannon, 1989a, 1989b; Davies et al., 1996; Nadeau et al., 1997). One article used the fastest of three trials,

however three of their participants completed just one trial due to their 10 metre assessment lasting longer than 30 seconds (Nakamura et al., 1985).

The usual assistive devices used by the participants, such as walking canes or orthoses, were allowed during the assessments in 13 studies (Bohannon, 1986a, 1989a, 1989b, 1992; Bohannon & Andrews, 1990; Bohannon & Walsh, 1992; Davies et al., 1996; Horstman et al., 2008; Lam et al., 2010; Lin, 2005; Nadeau et al., 1997; Ng & Hui-Chan, 2012; Severinsen et al., 2011). Four studies did not allow the use of any assistive devices (Dorsch et al., 2012; Lin et al., 2006; Nakamura et al., 1985; Nasciutti-Prudente et al., 2009) and four studies did not report if assistive devices were allowed or not during testing (Bohannon, 1991; Kobayashi et al., 2011; Liu-Ambrose et al., 2007; Maeda et al., 2000). It should be noted that, in the studies which allowed assistive devices, not all participants necessarily used such devices during their gait assessment. Eleven studies used HHD to measure isometric strength (Bohannon, 1986a, 1989a, 1989b; Dorsch et al., 2012; Kobayashi et al., 2011; Lam et al., 2010; Lin et al., 2006; Lin, 2005; Liu-Ambrose et al., 2007; Maeda et al., 2000; Nasciutti-Prudente et al., 2009), nine studies used laboratory-based dynamometers (Bohannon, 1992; Bohannon & Andrews, 1990; Bohannon & Walsh, 1992; Davies et al., 1996; Horstman et al., 2008; Nadeau et al., 1997; Nakamura et al., 1985; Ng & Hui-Chan, 2012; Severinsen et al., 2011) and one study used a combination of both (Bohannon, 1991).

3.4.3 Associations between isometric strength and gait velocity

A graphical representation of the correlation values between isometric muscle strength of the paretic limb and gait velocity recorded in each study is shown in Figure 3.2. Additional information regarding the correlations is presented in the appendices (Appendix A), along with the correlation values of the non-paretic limb. Thirteen articles exclusively measured the muscle groups around the knee (Bohannon, 1989a, 1991, 1992; Bohannon & Andrews,

1990; Bohannon & Walsh, 1992; Davies et al., 1996; Horstman et al., 2008; Kobayashi et al., 2011; Lam et al., 2010; Liu-Ambrose et al., 2007; Maeda et al., 2000; Nakamura et al., 1985; Severinsen et al., 2011), three measured only ankle muscle groups (Lin et al., 2006; Nadeau et al., 1997; Ng & Hui-Chan, 2012) and five studies measured muscle groups at the hip, knee and ankle (Bohannon, 1986a, 1989b; Dorsch et al., 2012; Lin, 2005; Nasciutti-Prudente et al., 2009). Mixed correlations were reported across the studies for correlations between gait velocity and the strength of the paretic hip flexors (correlation coefficients = 0.25 to 0.82) (Bohannon, 1986a, 1989b; Dorsch et al., 2012; Lin, 2005; Nasciutti-Prudente et al., 2009), hip extensors (correlation coefficients = 0.29 to 0.78) (Bohannon, 1986a, 1989b; Dorsch et al., 2012; Nasciutti-Prudente et al., 2009), hip abductors (correlation coefficients = 0.24 to 0.80) (Bohannon, 1986a, 1989b; Dorsch et al., 2012), knee extensors (correlation coefficients = 0.18 to 0.81) (Bohannon, 1986a, 1989a, 1989b, 1991, 1992; Bohannon & Andrews, 1990; Bohannon & Walsh, 1992; Davies et al., 1996; Dorsch et al., 2012; Horstman et al., 2008; Kobayashi et al., 2011; Lam et al., 2010; Lin, 2005; Liu-Ambrose et al., 2007; Maeda et al., 2000; Nakamura et al., 1985; Nasciutti-Prudente et al., 2009; Severinsen et al., 2011), knee flexors (correlation coefficients = 0.30 to 0.83) (Bohannon, 1986a, 1989b; Dorsch et al., 2012; Horstman et al., 2008; Nasciutti-Prudente et al., 2009) and ankle plantarflexors (correlation coefficients = 0.11 to 0.83) (Lin et al., 2006; Nadeau et al., 1997; Nasciutti-Prudente et al., 2009; Ng & Hui-Chan, 2012). In contrast, the strength of the ankle dorsiflexors of the paretic limb consistently showed moderate to strong associations with gait velocity (correlation coefficients = 0.50 to 0.77) (Bohannon, 1986a, 1989b; Dorsch et al., 2012; Lin et al., 2006; Lin, 2005; Nasciutti-Prudente et al., 2009; Ng & Hui-Chan, 2012). One study also measured the association between gait velocity and the strength of the hip adductors (correlation coefficient = 0.29), hip internal rotators (correlation coefficient = 0.30), hip external rotators (correlation coefficient = 0.22), ankle

invertors (correlation coefficient = 0.25), and ankle evertors (correlation coefficient = 0.33) (Dorsch et al., 2012). The non-paretic limb showed mixed correlations for each muscle group ranging from very weak to strong (correlation coefficients = 0.05 to 0.70) (see Appendix A).

Closer examination of the studies with larger sample sizes (Dorsch et al., 2012; Lam et al., 2010; Lin et al., 2006; Liu-Ambrose et al., 2007; Maeda et al., 2000; Ng & Hui-Chan, 2012; Severinsen et al., 2011) revealed very weak to moderate correlations between gait velocity and knee extensor strength (correlation coefficients = 0.18 to 0.55) (Dorsch et al., 2012; Lam et al., 2010; Liu-Ambrose et al., 2007; Maeda et al., 2000; Severinsen et al., 2011) and weak to moderate correlations for ankle plantarflexor strength (correlation coefficients = 0.29 to 0.58) (Dorsch et al., 2012; Lin et al., 2006; Ng & Hui-Chan, 2012). In contrast, ankle dorsiflexor strength consistently showed moderate to strong correlations with gait velocity (correlation coefficients = 0.50 to 0.73) (Dorsch et al., 2012; Lin et al., 2006; Ng & Hui-Chan, 2012).

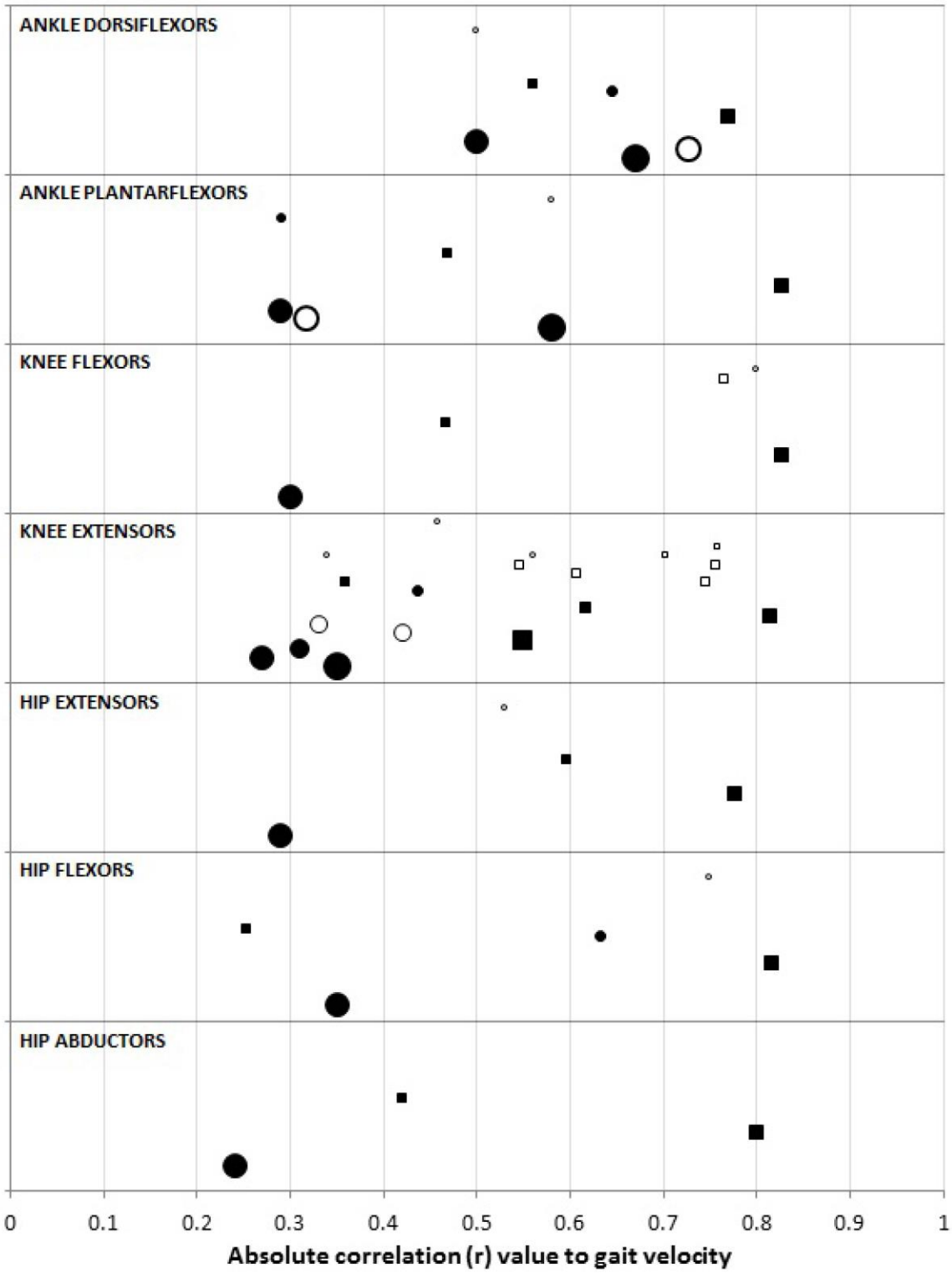

Figure 3.2. Associations between paretic lower limb isometric strength and gait velocity following stroke. All correlations are presented as absolute values. The size of the point indicates the sample size, with a larger point indicating a higher sample size. The y-axis is arranged such that low sample studies are towards the top of each muscle group section. Circular

points indicate participants with a mean time since stroke of greater than six months and square points indicate a mean time since stroke of less than six months. Solid points indicate the strength scores were normalised and open points indicate that strength scores were not normalised. One correlation value per muscle group from each study is provided. The associations of muscle groups only measured in one study (hip adductors, hip internal and external rotators, ankle invertors and ankle evertors) have not been presented in this figure to enhance the overall readability. Additional specific detail regarding the figure can be found in the appendices (Appendix A). Figure replicated with permission from Mentiplay et al. (2015a).

3.4.4 Quality assessment

The methodological quality scores for each study are shown in Table 3.5. The mean total score was 11.6 (range = 7.6 to 15.3; maximum of 20). Seven studies (Dorsch et al., 2012; Lam et al., 2010; Lin et al., 2006; Liu-Ambrose et al., 2007; Maeda et al., 2000; Ng & Hui-Chan, 2012; Severinsen et al., 2011) demonstrated the highest methodological quality scores in combination with the largest sample sizes. When compared to other articles included in this review, the quality scores and larger sample sizes could indicate that these studies were at less risk of bias, potentially enhancing the generalisability of their results. Overall, articles described outcome measures and the main findings of the study well. Additionally, studies also reported the r-value for each correlation, summarised results with reference to objectives and used appropriate statistical tests. Generally, studies provided little to no detail on the experience of assessors. Efforts to address bias (Severinsen et al., 2011) and justification of sample size (Lam et al., 2010) were only reported in single studies.

Table 3.5. Methodological quality assessment scores

Article	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total
Bohannon 1986a	0.5	0.5	1	0.8	1	1	1	0.5	1	1	0	0	1	0	0	0	0	0	0	0	9.3
Bohannon 1989a	0.5	0.5	1	0.8	0.5	0.5	1	0	1	0.5	0	0	1	1	1	0	0	0	0	0	9.3
Bohannon 1989b	1	0.5	1	0.8	1	0	1	0.5	1	0.5	0	0	1	1	0	0	0	0	0	1	10.3
Bohannon 1991	1	1	1	0.8	1	0.5	1	0.5	1	1	0.5	0	1	1	1	1	0	0	0	0	13.3
Bohannon 1992	0.5	1	1	0.8	1	0.5	1	1	1	0.5	0.5	0	1	1	1	0	0	0	0	0	11.8
Bohannon & Andrews 1990	1	1	1	0.8	1	0.5	1	0.5	1	1	1	0	1	1	1	0	0	0	0	0	12.8
Bohannon & Walsh 1992	0.5	1	1	0.8	1	0.5	1	0.5	1	0.5	1	0	1	1	1	0	0	0	0	0	11.8
Davies et al 1996	0.5	0.5	1	0.8	1	0.5	1	0	1	0.5	0.5	0	1	0	0	0	0	0	0	0	8.3
Dorsch et al 2012	0.5	1	1	0.8	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	1	15.3
Horstman et al 2008	1	1	1	1	1	0.5	1	0.5	1	1	0	0	1	0	0	0	0	0	0	0	10
Kobayashi et al 2011	0.5	1	1	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	12.5
Lam et al 2010	0.5	1	1	1	1	1	1	1	1	1	1	0	1	0	0	1	0	0	1	1	14.5
Lin et al 2006	0.5	1	1	0.8	1	1	1	0.5	1	1	0.5	0	1	1	0	0	0	1	0	1	13.3

Lin 2005	0.5	1	1	1	1	0.5	1	0.5	1	1	0.5	0	1	0	0	0	0	0	0	0	10
Liu-Ambrose et al 2007	0.5	1	1	0.8	1	1	1	0.5	1	1	1	0	1	1	0	0	0	0	0	1	12.8
Maeda et al 2000	0.5	0.5	1	1	1	0.5	1	0.5	1	1	0.5	0	1	1	0	0	0	0	0	1	11.5
Nadeau et al 1997	1	0.5	1	1	1	1	1	0.5	1	0.5	0.5	0	1	1	0	0	0	0	0	0	11
Nakamura et al 1985	0.5	0	1	0.6	1	0.5	1	0.5	1	0.5	0	0	0	0	0	0	0	1	0	0	7.6
Nasciutti-Prudente et al 2009	0.5	1	1	0.8	1	1	1	0.5	1	1	1	0	1	1	0	0	0	1	0	0	12.8
Ng & Hui-Chan 2012	0.5	1	1	0.8	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	1	12.3
Severinsen et al 2011	1	1	1	1	1	0.5	1	0.5	1	1	1	1	1	0	0	0	1	0	0	1	14

Note: Refer to Table 3.3 for the questions involved in the quality scores. Table replicated with permission from Mentiplay et al. (2015a).

3.5 Discussion

The results from this systematic review found a large range in correlation values between isometric strength and gait velocity in the stroke population. When considering those studies with a large sample size and high quality score, the strength of the ankle dorsiflexors was found to have the largest association with gait velocity when compared with other lower limb muscle groups. However, only seven articles included a large sample size and had a higher methodological quality score (Dorsch et al., 2012; Lam et al., 2010; Lin et al., 2006; Liu-Ambrose et al., 2007; Maeda et al., 2000; Ng & Hui-Chan, 2012; Severinsen et al., 2011), with only three of these articles actually measuring the strength of muscle groups around the ankle (Dorsch et al., 2012; Lin et al., 2006; Ng & Hui-Chan, 2012). The majority of studies only measured the strength of one muscle group, whereas the comparison of multiple muscle groups may assist in interpreting the relative importance of different muscle groups to gait velocity following stroke. The knee extensors were the most commonly measured muscle group, however the strength of the knee extensors demonstrated very weak to moderate associations with gait velocity in those seven articles with larger sample sizes and higher methodological quality. The results of this review did not support the hypothesis that the strength of the muscle groups most responsible for forward progression, including the ankle plantarflexors, would show strong associations with gait velocity than the other lower limb muscle groups. However, many of the included studies demonstrated incomplete reporting and inconsistencies with their methodology, suggesting caution when interpreting the results and highlighting the need for further research.

The moderate to strong correlation results between gait velocity and the strength of the ankle dorsiflexors was an unexpected finding. The ankle dorsiflexors act during the swing phase of gait to assist with ground clearance of the foot (Whittle, 2002; Winter, 1991). Weakness

of the ankle dorsiflexors may result in foot drop that can lead to compensatory movements, such as leg circumduction or pelvic hiking, to allow for foot clearance during gait (Whittle, 2002; Winter, 1991), therefore increasing swing time and potentially resulting in a reduction in overall gait velocity (Dorsch et al., 2012). Previous research has suggested a strong association between ankle dorsiflexor strength and stair climbing ability, the Timed Up and Go and the Six Minute Walk Test following stroke (Bonnyaud, Zory, Pradon, Vuillerme, & Roche, 2013; Ng & Hui-Chan, 2012, 2013). These previous associations support the importance of dorsiflexor strength in other functional activities. The correlations found in this review indicate that it may be pertinent to prioritise the measurement of ankle dorsiflexor strength in routine clinical assessment. Nevertheless, these results came from only three higher quality studies (Dorsch et al., 2012; Lin et al., 2006; Ng & Hui-Chan, 2012), two of which exclusively measured muscle groups around the ankle (Lin et al., 2006; Ng & Hui-Chan, 2012). It is recommended that future studies measure and compare multiple lower limb muscle groups to potentially highlight the relative contribution of each muscle group to gait velocity following stroke.

The strength of the ankle plantarflexors, hip flexors and hip extensors were not strongly correlated with gait velocity when compared to other lower limb muscle groups, despite the contribution these muscle groups make to forward progression. The ankle plantarflexors, hip flexors and hip extensors were infrequently measured (reported in seven, five and four articles respectively), which indicates further research is required. One study showed large correlation values between the strength of these muscle groups and gait velocity (correlation coefficients = 0.78 to 0.83) (Bohannon, 1989b). However, this study had relatively low methodological quality (scored 10.3 out of 20) and allowed the use of assistive devices during their gait assessment, which may have affected the results. This study also showed large correlations for all seven muscle groups assessed (correlation coefficients = 0.77 to

0.83) (Bohannon, 1989b), which were consistently larger than any other study included in this review. Of the seven articles with larger sample sizes and methodological quality, three measured the strength of the plantarflexors (Dorsch et al., 2012; Lin et al., 2006; Ng & Hui-Chan, 2012) and only one measured the hip flexors and extensors (Dorsch et al., 2012), further highlighting the need for high quality research in these potentially important muscle groups.

The strength of the knee extensors was the most commonly measured muscle group, reported in 18/21 studies. Four studies, with a relatively large sample size (n = 45 to 63) and higher methodological quality scores (12.8 to 15.3), showed a trend towards very weak to moderate associations between the knee extensors and gait velocity following stroke (correlation coefficients = 0.18 to 0.55) (Dorsch et al., 2012; Lam et al., 2010; Liu-Ambrose et al., 2007; Severinsen et al., 2011). The limited association results reported here may help to explain the findings of a recent systematic review, which showed that the majority of strength training interventions in neurological rehabilitation focus on training the knee extensors and that most of these interventions fail to result in significant improvement in gait performance (Williams et al., 2014b). The strength of the knee extensors has however been correlated with performance in other functional assessments such as stair climbing (Bonnyaud et al., 2013; Flansbjer et al., 2006) and sit-to-stand ability (Lomaglio & Eng, 2005). The association between knee extensor strength and other functional tasks suggests that this muscle group should not be overlooked in assessment and treatment following stroke. However, the results from the current review imply that, when considering gait velocity, it may be warranted to emphasise the assessment of other lower limb muscle groups and not just solely the knee extensors.

The use of assistive devices (e.g. walking sticks or ankle foot orthoses) during gait assessment was allowed in 13 of the included studies. The use of such devices, especially ankle foot orthoses, can change the contributions a muscle group makes during gait (Dorsch et al., 2012). Even the use of simple assistive devices such as walking sticks, can influence kinematic and spatial variables during gait, therefore potentially affecting the association between strength and gait velocity (Kuan et al., 1999). Comparison between those articles which allowed assistive devices with those that did not was not feasible. Most articles that included assistive devices pooled the results from all participants, regardless of the type of assistive device used or if assistive devices were used at all. This could potentially detract from the generalisation of results from the studies that did not account for the use of assistive devices in their analysis. The inclusion of participants who required assistive devices may have resulted in participants with more severe physical deficits, thus making the sample more representative of the wider stroke population. However, the inclusion of these data without further clarification indicates care may be needed when interpreting their results due to the differences between participants.

There was also variation in the studies as to the speed of gait assessment, with participants either being asked to walk at a comfortable pace or as fast as safely possible. Three studies asked their participants to perform the gait assessment at both speeds (Bohannon, 1992; Bohannon & Walsh, 1992; Nadeau et al., 1997) and found little difference between the correlations for the different paces. Despite this, the small sample size in these three studies (each $\leq$ 20 participants) negated the ability to determine the differences in correlations between the studies for both gait speeds. Variation also existed in the strength assessment device, with one study employing both a laboratory-based, fixed dynamometer as well as a HHD (Bohannon, 1991). This study found minimal differences in the correlation to gait velocity between the two strength devices (Bohannon, 1991). This could indicate that it is

adequate to use clinically-based measures of isometric muscle strength when examining the correlations between muscle strength and gait velocity after stroke. However, further high quality research would be needed to determine if the association with gait velocity is altered depending on the either the speed of the gait assessment or the strength assessment device used.

The current systematic review did not examine isokinetic strength assessment, which may provide additional information on the correlations between muscle strength and gait velocity following stroke. Previous research with a relatively large sample size ($n \geq 50$) has examined the associations between isokinetic lower limb strength and gait velocity following stroke and found similar results to this review, with isokinetic knee extensor strength showing weak to moderate associations with gait velocity (Flansbjer et al., 2006; Patterson et al., 2007). Assessment of isokinetic strength requires expensive and cumbersome motorised dynamometers which were excluded from the current review as many rehabilitation centres or hospitals do not have access to such equipment.

The relatively low sample size of the majority of the studies included in this review is a major limitation of the included studies. Inclusion of a reasonable sample size in correlation studies is vital to ensure reasonable variation within the data to allow for accurate correlation analyses and so that the study is statistically powered to detect a significant association (Portney & Watkins, 2009). Accordingly, Portney and Watkins (2009) suggest a sample size of 28 is required to detect a moderate correlation (r-value of 0.50), powered at 80% with a two tailed significance level of 0.05. In the current review, only eight studies included a sample size of 28 or above (Bohannon, 1989b; Dorsch et al., 2012; Lam et al., 2010; Lin et al., 2006; Liu-Ambrose et al., 2007; Maeda et al., 2000; Ng & Hui-Chan, 2012; Severinsen et al., 2011) and only one study provided a power calculation for their sample (Lam et al.,

2010). As such, more weight could be placed on the results from these studies as they were adequately powered to detect a significant moderate correlation.

Many of the included studies also failed to adequately report the characteristics of their participants. A clear description of participant characteristics is required to allow clinicians and researchers the ability to interpret and generalise the results. Most studies failed to report the type of stroke (i.e. haemorrhagic or ischaemic). Other areas of poor reporting included limited information on the reliability of the strength assessment device or the assessor, which is particularly important when using HHD. While this review highlights some important results regarding the associations between isometric strength and gait velocity following stroke, further research is required. It would be beneficial for future studies to ensure a complete participant characteristic description, measure multiple lower limb muscle groups, provide reliability results of their strength assessment and to include an adequately powered sample size to address some of the inconsistencies in the current literature.

It should be noted that one of the higher quality articles included in this review that assessed ankle muscle strength, included only participants that had confirmed spasticity of the ankle plantarflexors (Ng & Hui-Chan, 2012). The results from this study found similar correlations to those found in two other studies (Dorsch et al., 2012; Lin et al., 2006), despite the two other studies not purposefully selecting participants with ankle spasticity. The other articles (Dorsch et al., 2012; Lin et al., 2006) measured the same muscle groups and had similar sample sizes to that by Ng and Hui-Chan (2012), indicating that spasticity may not necessarily affect the association between strength and gait velocity. Further targeted research is warranted to conclusively determine the impact of spasticity on correlations between strength and gait velocity following stroke.

3.5.1 Limitations

It would be erroneous to imply that the muscles of the lower limb work in isolation and that weakness in one muscle group is solely responsible for reduced gait velocity following stroke. Nonetheless, before attempting to understand the contribution of other factors, such as balance or proprioception, it may be important to first investigate the associations between gait velocity and single variables, such as the strength of individual muscle groups.

The development and use of the customised quality assessment tool, without assessing the psychometric properties of the tool, is a limitation of the review. At the time of this review there were no other appropriate tools to assess methodological quality of articles with various research designs that examine correlations, necessitating the modification of the tool described by Tan et al. (2012).

The inclusion of articles with heterogeneous participant characteristics (e.g. time since stroke and use of assistive devices) may be problematic due to the inability to make direct comparisons between the included articles, however this review is the first to collate and compare results from articles examining the associations between isometric strength and gait velocity after stroke. It was decided to include all articles regardless of the included participant characteristics. The results from this initial step to understand the associations between muscle strength on gait velocity may help to guide the assessment and treatment plans for clinicians and researchers as well as create a solid platform for future research on this topic.

This systematic review only examined bivariate correlations between isometric strength and gait velocity. Multivariable regression analyses may provide additional information about the relationship between strength and gait velocity following stroke. It was decided to only

focus on bivariate associations for the purposes of this review, as a synthesis of regression results is problematic, due to the various covariates included in regression models, when attempting to compare the relative influence of each lower limb muscle on gait velocity. Further research is required to collate results from regression analyses that examined the relationship between isometric strength and gait velocity following stroke.

3.6 Conclusion

The measurement of lower limb strength following stroke is an important consideration that is often implemented in research and clinical practice. Whilst this review suggests that the strength of the ankle dorsiflexors has a greater association with gait velocity compared with other muscle groups, the results should be interpreted with caution due to identified limitations in the included studies. Further high quality research, with complete reporting and a larger sample size, is needed to determine the association and potential effect of muscle weakness on gait velocity following stroke.

With regards to the implications of this review, the lack of high quality research in this area needs to be addressed. The current study helped inform the design of Study Three of this thesis in particular, to ensure that participant characteristics are described adequately, that multiple lower limb muscle groups are measured, that reliability of the strength assessor is examined and that an adequately powered sample is included. The results from this systematic review highlight that the measurement of knee extensor strength during rehabilitation may not be related to changes in gait velocity following stroke. Other muscle groups need to be considered for assessment and treatment in post-stroke rehabilitation.

CHAPTER FOUR: LOWER LIMB ISOMETRIC STRENGTH AND POWER USING HAND-HELD DYNAMOMETRY: A RELIABILITY AND VALIDITY STUDY (STUDY TWO)

4.1 Preamble

Study One highlighted the need for further high quality research to examine the associations between muscle strength and gait velocity following stroke. Prior to this program of research addressing the current gap in previous research, Study Two was undertaken to examine the psychometric properties of HHDs for the assessment of isometric muscle strength. The purpose of Study Two was to determine the reliability and validity of the HHD strength and RFD measures taken by the assessor responsible for data collection in the subsequent studies (thesis author BFM). Furthermore, this study sought to contrast the reliability and validity of strength and RFD measures derived from two different HHDs to assist with identifying the most appropriate device to use for the subsequent studies. Previous research has also shown that muscle power may be a better predictor of physical function than muscle strength in a range of clinical populations (Maffiuletti et al., 2010; Moreau et al., 2012; Pohl et al., 2002; Reid et al., 2015; Winters et al., 2014). Despite the importance of muscle power, the majority of studies have measured muscle power using equipment that has limited clinical accessibility such as laboratory-based fixed dynamometers or force plates. Study Two was designed to examine the psychometric properties of HHDs, for measurement of isometric muscle strength as well as isometric power. This study was necessary to determine the reliability and validity of HHD for strength and power assessment before use in the stroke

cohort. This chapter presents the findings of a peer-reviewed manuscript, which has been adapted with permission for this thesis. The manuscript has been published in *PLOS ONE* (Mentiplay et al., 2015b) with the full text in Appendix G.

4.2 Introduction

A lack of muscle strength is a limitation that is commonly observed in a range of clinical populations, such as stroke and cerebral palsy, and has been documented to impact upon physical function (Bohannon & Walsh, 1992; Doherty, 2003; Gerrits et al., 2009; Wiley & Damiano, 1998). Whilst muscle strength (the peak amount of force a muscle group can produce) is often assessed and treated in neurological rehabilitation (Williams et al., 2014b), another important clinical consideration is how rapidly that force can be produced (i.e. muscle power) (Aagaard et al., 2002; Gerrits et al., 2009). Following stroke, muscle power is reduced in both the upper and lower limbs of the paretic side when compared with the non-paretic limb and with healthy controls (Canning et al., 1999; Fimland et al., 2011; Gerrits et al., 2009; Knight et al., 2014; Pohl et al., 2002; Stavric & McNair, 2012). Previous research in elderly populations suggests that muscle power is more strongly associated with self-reported function, incidence of falls and physical performance than muscle strength (Bean et al., 2002; Fleming et al., 1991; Foldvari et al., 2000; Skelton et al., 2002). As such, clinicians potentially need to consider both muscle strength and power for assessment and treatment during stroke rehabilitation.

Muscle power can be measured using many different methods. Devices that are capable of assessing muscle power include, but are not limited to, linear position transducers (Alemany et al., 2005; Garnacho-Castaño et al., 2015; Stavric & McNair, 2012; Villadsen et al., 2012) and force plates (Davies et al., 1983; McMaster et al., 2014; Stavric & McNair, 2012). However, the high cost, time demands and accessibility of such devices may limit their use

in clinical settings. Additionally, the procedures involved in assessment with these devices require movements with high physical demands performed on cumbersome and bulky equipment, which may limit their suitability in the stroke population.

A commonly used measure of explosive muscle strength or isometric muscle power that may be more suited to the stroke population is RFD, which can be calculated during an isometric contraction as the change in force over a certain time period (Δforce/Δtime) (Aagaard et al., 2002; Caserotti et al., 2008). This measure of isometric muscle power has important functional implications; sufficient RFD is required to perform quick and forceful contractions such as those seen during walking (Aagaard et al., 2002). Initial research in the stroke population examining the association between RFD and functional measures has indicated that RFD provides a stronger association with gait velocity following stroke compared with muscle strength (Pohl et al., 2002), which highlights the importance of the measurement of isometric muscle power.

There are currently many methods used to calculate RFD from isometric contractions (Maffiuletti et al., 2016). Such methods involve measuring the change in force over the change in time from the onset of contraction to time intervals such as 30, 50 or 100ms (Aagaard et al., 2002; Andersen & Aagaard, 2006; Suetta et al., 2004). This method of determining the onset of contraction has been used widely (Maffiuletti et al., 2016), however the onset of contraction has been defined in different ways, including when the force trace exceeds a set threshold of either absolute (e.g. 5N) or relative values (e.g. percentage of peak force) (Aagaard et al., 2002; Andersen & Aagaard, 2006; Andersen et al., 2010; Blazevich et al., 2008; Pijnappels et al., 2008). Other methods of RFD calculation include the examination of successive time intervals (e.g. 5ms) during the initial rise in force to determine the peak RFD across the entire trial (Bemben et al., 1991; Korhonen et al., 2006;

Kyröläinen et al., 2005), or calculating RFD between percentages of peak force (e.g. between 30 and 60% of peak force) (Sleivert & Wenger, 1994). There is currently no consensus as to which RFD calculation should be used for the measurement of isometric muscle power.

The criterion-reference assessment of both isometric muscle strength and RFD involves fixed laboratory-based dynamometry. However, such laboratory-based dynamometers have similar limitations to other measurement devices of muscle power in that these dynamometers are expensive and cumbersome, which may preclude their use in a clinical setting for routine assessment (Kolber & Cleland, 2005; Moriello & Mayo, 2006; Stark et al., 2011). Clinic-based assessment of muscle power is important to allow for widespread access to inform the development of management plans. Devices such as HHD are considered an appropriate and convenient device to assess isometric muscle strength in a clinical setting due to their relatively low cost, portability and strong reliability and validity compared with laboratory-based dynamometers (Bohannon, 2012; Kolber & Cleland, 2005; Moriello & Mayo, 2006; Stark et al., 2011; Trudelle-Jackson, Jackson, Frankowski, Long, & Meske, 1994). A recent systematic review identified 13 different versions of HHDs used previously to assess isometric strength (Bohannon, 2012), although currently little comparison has been performed as to which commercially available HHD is the most reliable and valid. To date, no study has examined the psychometric properties of HHD for the assessment of RFD.

The overall aim of this study was to determine the psychometric properties of HHD for assessment of isometric muscle strength and power. Specific aims of this study were to: 1) examine the reliability of different algorithms for the calculation of RFD using fixed laboratory-based dynamometry; 2) assess the intra-rater, inter-rater and inter-device

reliability of two commercially available versions of HHD for the assessment of isometric lower limb muscle strength and RFD; and 3) determine the concurrent validity of these two versions of HHD compared with a laboratory-based fixed dynamometer for the assessment of lower limb muscle strength and RFD.

4.3 Methods

4.3.1 Participants

A convenience sample of participants over the age of 18 years who were healthy and unimpaired had their isometric lower limb muscle strength and RFD assessed. Participants were included if they had no lower limb injury in the preceding two months and had no other comorbidities, such as cardiovascular or respiratory conditions, that could potentially impact on the assessment of muscle strength or power. It was deemed unrealistic to recruit participants following stroke for this study due to the time demands and numerous MVCs required during testing. This study utilised a concurrent validity, test-retest reliability design where participants attended two identical testing sessions. The study had approval from the Australian Catholic University Human Research Ethics Committee (see Appendix H). The healthy sample was recruited from the body of students and staff at the Australian Catholic University. Prior to testing, all participants were provided with study details and gave written informed consent. Characteristics collected from these participants included age, gender, height and weight.

The sample size required for this study was calculated using estimates of the expected and acceptable values of ICCs for both reliability and validity. Portney and Watkins (2009) suggest that ICC values greater than 0.75 should be interpreted as indicating good reliability. For the analysis of the current study, we deemed an ICC confidence interval of ± 0.1 to be

the maximum preferred value, and therefore to ensure our true ICC value exceeded the set threshold of 0.75, this study was powered to detect an ICC of 0.85 with a confidence interval of ± 0.1. Consequently, based on a power calculation performed in accordance with de Vet, Terwee, Mokkink, and Knol (2011), 30 participants were required.

4.3.2 Instrumentation

Methods using laboratory-based fixed dynamometry, force platforms, 1RM testing and linear position transducers have all been used previously to quantify strength and power. Despite the wide range of available assessments, the focus of this thesis is on clinically feasible devices to allow for the potential translation of this research into routine practice. The decision was made to use HHDs for assessment of isometric strength and power due to the relatively inexpensive price of such devices, the minimal equipment required, the ease of testing for participants and the previously reported strong reliability and validity in healthy and clinical populations (Bohannon, 2012; Stark et al., 2011).

Two commercially available versions of HHD were used to assess lower limb isometric strength and RFD: the Lafayette Manual Muscle Testing System Model-01165 (Lafayette Instrument Company, Lafayette IN, USA) and the Hoggan micro*FET*2 (Hoggan Scientific, LLC, Salt Lake City UT, USA). These two types of HHD remained as purchased from each manufacturer with no modification to the device. At the time of testing, the approximate retail cost of the Hoggan device was US$1,095 (plus US$495 for the software package), with the Lafayette device costing approximately US$1,200 (software included in the purchase price). These devices were chosen as they are the two most commonly used HHDs in the previous literature (Bohannon, 2012) and are frequently used in clinical practice. Both HHDs provide instantaneous feedback of isometric muscle strength (peak force reading across the trial) via LED displays. To allow for calculation of RFD, the time series of the

raw force data needed to be downloaded through additional software packages. The Lafayette device has on-board memory capabilities that allow for the storage of up to 150 trials during testing, after which the raw data can be downloaded via Bluetooth to a computer running their included software. To extract the raw data from the Hoggan device, it needs to be connected wirelessly to a computer running their software package (not included in the price of the HHD) during assessment.

To examine inter-rater reliability, two assessors measured the isometric strength and RFD of all participants using both HHDs. The two assessors were male and had experience in using HHDs, with Assessor-A having one year of experience with HHDs (thesis author BFM) and Assessor-B having 10 years of clinical physiotherapy experience that included the use of HHDs (publication co-author LGP). To assess the concurrent validity of the HHDs against a criterion reference, the KinCom isokinetic dynamometer (Chattex Corporation, Chattanooga TN, USA) was used. Laboratory-based dynamometers vary in price with the usual retail cost in excess of US$50,000. These devices are often considered the 'gold standard' of strength assessment, with the KinCom being used in previous HHD validation studies (Stark et al., 2011). All dynamometers recorded force in kilograms and were calibrated once prior to commencing the study.

4.3.3 Procedures

Only the isometric strength and power of lower limb muscle groups were assessed in this thesis as it is logical to hypothesise that lower limb strength and power will have a stronger association with measures of gait function compared to upper limb muscle groups. There is currently no clear consensus on the most appropriate testing positions for HHDs, which was demonstrated by a systematic review highlighting a range of methodologies used for lower limb HHD assessment (Stark et al., 2011). Based on previous research and pilot work prior

to this study, the positions shown in Figure 4.1 were implemented. These testing positions have shown strong reliability for the measurement of isometric strength for the hip (Thorborg, Petersen, Magnusson, & Hölmich, 2010), knee (Bohannon, 1986b) and ankle (Bohannon, 1986b) muscle groups.

To provide a comprehensive assessment of lower limb strength and power, eight lower limb muscle groups were assessed. The participants were assessed in three positions (seated, supine and prone): hip flexors, knee extensors and knee flexors were assessed in a seated position; ankle plantarflexors, ankle dorsiflexors, hip abductors and hip adductors in a supine position; hip extensors in a prone position. These positions were chosen to minimise position changes for the participant and therefore enhance feasibility of testing in this manner in a clinical setting for the stroke population in the subsequent studies. The muscle groups chosen for assessment were those commonly reported in the stroke literature examining the associations between strength and gait velocity (Study One).

Assessment of HHD was conducted first. The order was randomised as to which assessor and HHD was used first, however the order of the muscle groups was kept consistent (order demonstrated in Figure 4.1). To illustrate this, if the Lafayette and Assessor-A was randomised to be first, all seated muscle groups would be assessed with the Lafayette followed by seated muscle groups with the Hoggan device, then all supine muscle groups with the Lafayette then Hoggan and lastly the prone muscle groups with the Lafayette then Hoggan. Following a rest period of 5 minutes, the same protocol was repeated by Assessor-B. During pilot testing, the assessment of very strong muscle groups, namely the knee extensors and ankle plantarflexors, proved problematic. Previous research has used stabilisation of HHDs, where a belt is attached to a fixed structure that removes the need for the assessors to produce any force at all (Bohannon, 2012). The use of belt stabilisation may

reduce the clinical utility of HHDs and was not used in this thesis. For the current study, to assist the assessor in overcoming the force produced by the participant for these muscle groups, the plinth was placed close to a wall, which aided the assessors in their resistance of the force produced by the participants (see Figure 4.1).

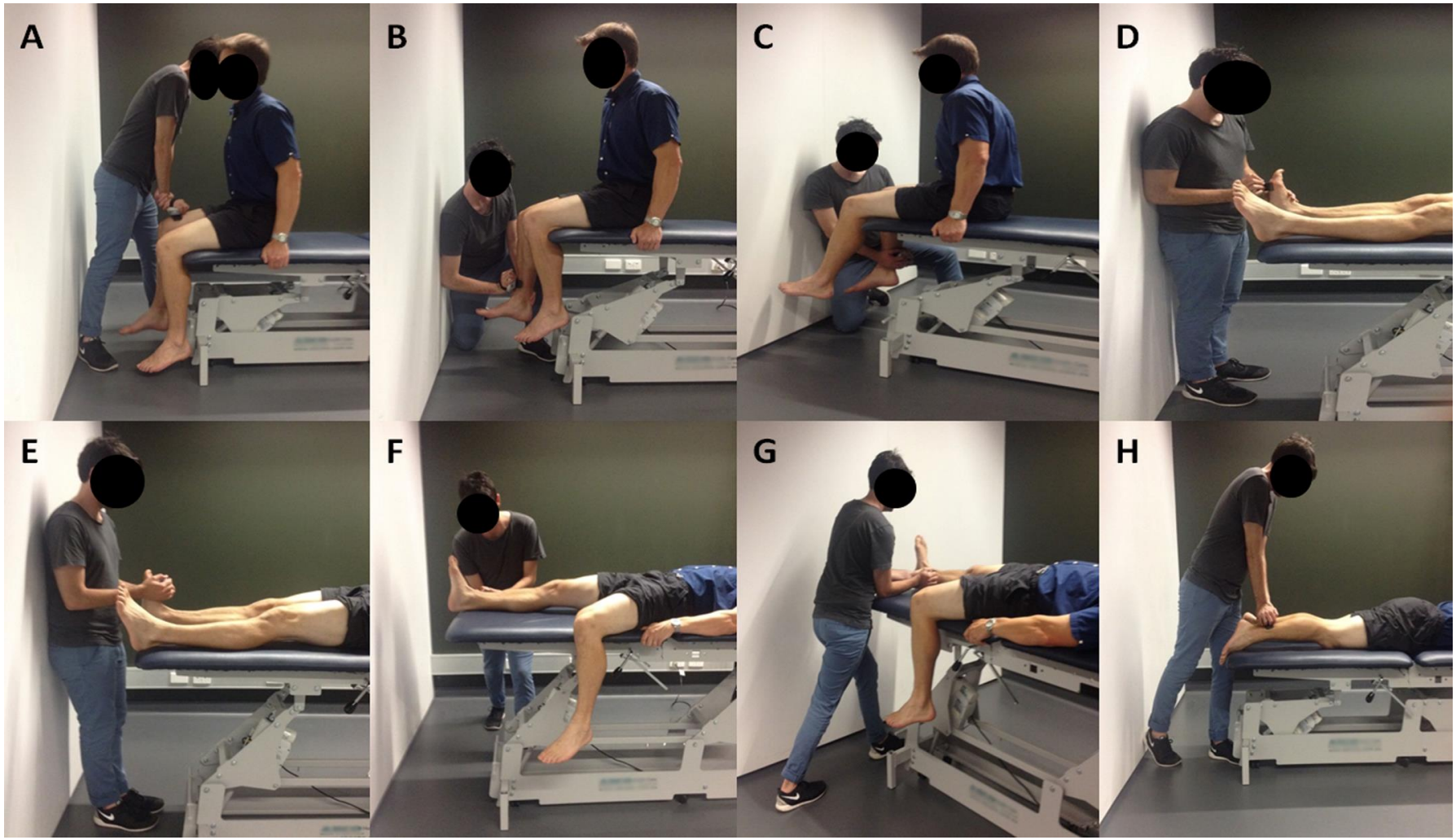

Figure 4.1. Assessment of isometric strength and power using hand-held dynamometry. The same testing positions were used for the KinCom fixed dynamometer. These positions were kept consistent across all studies. **A)** Hip flexion – seated with hips and knees at 90°. Dynamometer on

anterior aspect of thigh, proximal to knee joint. **(B)** Knee extension – seated with hips and knees at 90°. Dynamometer on anterior aspect of shank, proximal to ankle joint. **(C)** Knee flexion – seated with hips and knees at 90°. Dynamometer on posterior aspect of shank, proximal to ankle joint. **(D)** Ankle plantarflexion – supine with hips and knees extended and ankle in plantigrade. Dynamometer on metatarsal heads on the sole of the foot. **(E)** Ankle dorsiflexion – supine with hips and knees extended and ankle relaxed. Dynamometer on metatarsal heads on the dorsum of the foot. **(F)** Hip abductors – supine with hips and knees extended. Dynamometer placed on lateral aspect of shank, proximal to ankle joint. **(G)** Hip adductors – supine with hips and knees extended. Dynamometer placed on medial aspect of shank, proximal to ankle joint. **(H)** Hip extensors – prone with hips and knees extended. Dynamometer placed on posterior aspect of shank, proximal to ankle joint. Figure replicated with permission from Mentiplay et al. (2015b).

Following HHD testing, the KinCom fixed dynamometer was used to assess isometric strength and power utilising the same positions described for HHD. The order of muscle groups assessed on the KinCom was different to that used during HHD testing, to reduce the time requirements of testing due to difficult nature of moving the KinCom into the various positions and needing to use different attachments. The order for the KinCom was as follows: knee extensors, knee flexors, hip flexors, hip abductors, hip adductors, hip extensors, ankle plantarflexors and ankle dorsiflexors. The relevant ankle attachment was used on the KinCom for the assessment of ankle muscle groups.

All tests involved the participant performing MVCs. Instructions provided to the participants for every trial were 'at the count of three, push/pull as hard and as fast as you can and hold that contraction until I say relax'. Each test lasted between 3 to 5 seconds and ended after a steady maximal force was produced. To provide stabilisation, participants were instructed to hold the side of the plinth during testing. Constant verbal instruction was given throughout the testing. Only the right limb of each participant was assessed to reduce fatigue and the time demands of testing. A submaximal practice was given for each muscle group for both HHDs and the fixed dynamometer to ensure the participant understood the task required. Two maximal trials were recorded for each muscle group.

4.3.4 Data analysis

A custom-written software program (LabVIEW 2009 National Instruments, Austin TX, USA) was made to analyse the raw data from the three devices using the following procedures. A zero-phase shift 10Hz lowpass 4^{th} order Butterworth filter was applied to data from each of the three devices. Due to differences in sampling rates between devices (Lafayette: stable 40Hz; Hoggan: unstable, approximately 100Hz; KinCom: stable 1000Hz), the data from the HHDs were resampled to a constant interval 1000Hz using cubic spline

interpolation to allow for consistent and unbiased analysis. Whilst normalisation to the length of the lever arm to calculate torque, as well as normalising the torque values to body mass, is important to allow the comparison of results between participants, data from this study were not normalised due to the analysis only involving comparisons within participants and thus normalisation was deemed redundant for this study. These steps of normalisation were performed later in Study Three and Four when comparing participants following stroke.

Isometric muscle strength was calculated by measuring peak force, which was determined by calculating the highest force value recorded (in kilograms) during both trials for each muscle group. There is currently no consensus as to the most appropriate measure of RFD. Therefore, a comparison of the reliability of the results from the KinCom dynamometer using different methodologies was included in this study. A commonly used method that was not assessed in Study Two involves determining the RFD from onset of contraction to a set time interval (e.g. onset to 50 or 100ms). However, the determination of onset of contraction can be calculated using different automated thresholds (e.g. absolute force/torque values such as 7.5 Nm or relative to individual peak force such as 2% of peak force) or visual/manual identification of the onset of force (Maffiuletti et al., 2016). There are potential errors in both methods for identification of onset of contraction depending on the baseline noise of the dynamometer if using automated methods or subjectivity problems with manual identification (Maffiuletti et al., 2016). Additionally, identifying the onset has been labelled arbitrary (Pua et al., 2009) and is especially problematic when considering the use of HHD as there is the potential for the thresholds for onset to be reached whilst the HHD pad is placed on the lower limb just prior to the participant performing the actual contraction. Despite the method of determining onset of contraction being commonly used (Maffiuletti et al., 2016), this thesis did not calculate RFD in this manner.

To include a comparison of differing methods of RFD calculation, variants of three methods for the assessment of isometric muscle power were included: 1) time to peak force; 2) calculating peak RFD between percentages of the peak force (5 to 95%, 10 to 90%, 15 to 85%, 20 to 80%, 25 to 75%, 30 to 70%, 35 to 65%, 40 to 60%); and 3) examining successive time intervals (e.g. sample 1 to 11, 2 to 12, 3 to 13 etc.) during the initial rise in force to determine the peak RFD across the trial for time intervals of 10, 20, 50, 100 and 200ms. The first method of time to peak force has been used previously as an indicator of isometric power but is a poor measure due to the fluctuation in force readings during the plateau of an isometric force curve (see Section 2.4 for further details). The next two methods differed in that the percentage of peak force method has a fixed position on the force trace but a variable time interval (i.e. it is always between the set force thresholds such as between 20 and 80% of peak force, but the duration shortens if the RFD is higher), whilst the successive time intervals method has a fixed time interval but variable force position (i.e. the extracted data always has the same number of samples in it such as 200ms, but it could occur anywhere on the ascending slope of the force trace). Of the two recorded trials for each muscle group, the highest peak RFD value across the trials was used for analysis.

4.3.5 Statistical analysis

Data were assessed for normality using a Shapiro-Wilk test, to ensure the data conformed to a normal distribution. Descriptive statistics (mean and standard deviations) were used to describe participant demographics and anthropometrics as well as variables of peak force and RFD for each lower limb muscle group.

The first step in analysis was to calculate the test-retest reliability of different RFD algorithms from the fixed KinCom dynamometer, which was done using a two-way random effects model $ICCs_{(2,k)}$ with 95% confidence intervals. These ICCs include systematic error,

with k representing the average of k scores from each participant. To compare the reliability between algorithms, median and interquartile ranges were calculated as aggregates of each muscle group for the different RFD algorithms (i.e. the median and interquartile range of eight muscle groups for RFD-10ms, median and interquartile range for RFD-20ms etc.).

The second step was assessment of intra-rater reliability of each of the three devices as well as inter-rater and inter-device reliability of the HHDs. Intra-rater and inter-rater reliability was assessed using ICCs, standard error of measurement (SEM) and minimal detectable change (MDC) with 95% confidence intervals. The association and agreement between assessors and devices, for inter-rater and inter-device reliability, were also measured using Pearson's correlation and concordance correlation coefficients. The Pearson's correlation coefficient assesses the association irrespective of magnitude differences whereas the concordance coefficient assesses association and deviations from the line of identity (y = x).

The SEM and MDC were calculated from formulas provided by Portney and Watkins (2009) and expressed as percentages of the mean. The SEM provides an indication as to what can be considered measurement error whilst the MDC reflects the amount of change required to indicate that the change is not a result of the measurement error. The SEM was calculated by multiplying the standard deviation of the first session results by the square root of one minus the ICC ($SEM = SD\sqrt{1 - ICC}$) (Portney & Watkins, 2009). The MDC was calculated using the following formula: $MDC = z \times SEM \times \sqrt{2}$, where z = 1.96 (based on 95% confidence) (Portney & Watkins, 2009).

The last step in analysis was to examine the concurrent validity of HHDs compared to the criterion reference laboratory-based KinCom dynamometer. This was done using ICCs, Pearson's correlation and concordance correlation coefficients. Additional analysis of validity was completed using Bland-Altman plots with 95% limits of agreement (Ludbrook,

2010). Standard or regression-based (when proportional bias was detected) Bland-Altman plots were created for all variables. Correlations of the difference between scores and the average scores were examined to detect a proportional bias ($r > 0.50$), which indicated use of a regression-based Bland-Altman plot.

Point estimates of the ICC values for reliability and validity were based on those provided by Portney and Watkins (2009) and interpreted as poor (< 0.50), moderate (0.50 to 0.74), good (0.75 to 0.89) and excellent (≥ 0.90). All statistical analyses were performed using Microsoft Excel (Microsoft Corporation, Redmond, WA USA) or the Statistical Package for Social Sciences version 23 (IBM Corp., Armonk, NY USA).

4.4 Results

A convenience sample of 30 participants (age: 22.87 ± 5.08years, mass: 68.67 ± 9.15kg, height: 172.85 ± 9.11cm, gender: female 15) attended two identical testing sessions one week apart (mean: 7 ± 2days). One participant was unable to attend the second session due to other commitments. On many occasions the Hoggan software failed to save the raw data during testing, resulting in fewer data sets for all analyses involving the Hoggan device. The KinCom was unable to be used at all for four participants as the device was being repaired (the mechanism that moved the seat and dynamometer into position), which resulted in a lower sample size for concurrent validity analyses. Further explanation of missing data is provided in the appendices (Appendix B).

4.4.1 Reliability of different RFD algorithms

Table 4.1 provides the test-retest reliability for all muscle groups for each measure of RFD. The first two measures of RFD calculated, 1) time to peak force; and 2) measuring peak RFD between percentages of the peak force (5 to 95%, 10 to 90%, 15 to 85%, 20 to 80%,

25 to 75%, 30 to 70%, 35 to 65%, 40 to 60%), demonstrated poor to good test-retest reliability (median ICCs = 0.43 to 0.84) on the fixed KinCom dynamometer. In contrast, the third measure of RFD, 3) examining successive time intervals (e.g. sample 1 to 11, 2 to 12, 3 to 13 etc.) during the initial rise in force to determine the peak RFD across the trial for time intervals of 10, 20, 50, 100 and 200ms, showed excellent test-retest reliability (median ICC = 0.91 to 0.93). For each time interval, the 200ms method had the highest median reliability results (median ICC = 0.93) with no results for each muscle group lower than the threshold for good reliability ($\geq$ 0.75); therefore, this method was used to calculate RFD for the remainder of this study as well as Study Three and Four.

Table 4.1. Test-retest reliability of different rate of force development measures for the KinCom

	Time to peak	Percentage of peak force RFD measures								Successive time intervals peak RFD measures				
		5-95%	10-90%	15-85%	20-80%	25-75%	30-70%	35-65%	40-60%	10ms	20ms	50ms	100ms	200ms
ADF	-0.93	0.24	0.49	0.71	0.70	0.65	0.63	0.63	0.62	0.64	0.65	0.62	0.72	0.77
APF	0.67	0.95	0.96	0.97	0.95	0.87	0.85	0.88	0.88	0.96	0.96	0.96	0.95	0.95
HAB	-0.47	-0.22	0.45	0.59	0.77	0.82	0.81	0.79	0.83	0.83	0.83	0.86	0.90	0.88
HAD	0.46	0.47	0.62	0.56	0.59	0.75	0.74	0.77	0.77	0.78	0.79	0.80	0.88	0.92
HE	0.40	0.41	0.17	0.26	0.54	0.57	0.84	0.79	0.85	0.91	0.91	0.91	0.91	0.87
HF	0.70	0.77	0.92	0.94	0.95	0.95	0.94	0.94	0.94	0.95	0.95	0.95	0.95	0.94
KE	0.75	0.82	0.83	0.91	0.91	0.92	0.91	0.90	0.90	0.97	0.97	0.97	0.97	0.98
KF	0.39	0.77	0.84	0.78	0.73	0.70	0.66	0.66	0.67	0.93	0.93	0.92	0.89	0.93
Median	0.43	0.62	0.73	0.75	0.75	0.79	0.83	0.79	0.84	0.92	0.92	0.92	0.91	0.93
IQR	0.18-0.68	0.37-0.78	0.48-0.86	0.58-0.92	0.67-0.92	0.69-0.88	0.72-0.87	0.74-0.89	0.75-0.89	0.82-0.95	0.82-0.95	0.85-0.95	0.89-0.95	0.88-0.94
N = < 0.75	7	4	4	4	4	3	3	2	2	1	1	1	1	0

Note: RFD = rate of force development; ADF = ankle dorsiflexors; APF = ankle plantarflexors; HAB = hip abductors; HAD = hip adductors; HE = hip extensors; HF = hip flexors; KE = knee extensors; KF = knee flexors; IQR = interquartile range (25-75%); N = < 0.75 = number of muscle groups below the threshold of good reliability of 0.75. Table adapted with permission from Mentiplay et al. (2015b).

4.4.2 Intra-rater, inter-rater and inter-device reliability

The mean, standard deviation and intra-rater reliability results for peak force and RFD are shown in Table 4.2 and Table 4.3 respectively. Intra-rater reliability was good to excellent (ICC $\geq$ 0.75) for all peak force measures with the exception of a moderate result for the ankle plantarflexors measured by Assessor-B with the Hoggan HHD (ICC = 0.74). Intra-rater reliability was also good to excellent (ICC $\geq$ 0.75) for all RFD measures with the exception of the knee extensors measured by Assessor-A with the Hoggan HHD (ICC = 0.71) and measures of ankle dorsiflexors (ICC = 0.49), hip abductors (ICC = 0.74) and knee extensors (ICC = 0.71) by Assessor-B with the Lafayette HHD.

Table 4.2. Mean, standard deviation and intra-rater reliability for each assessor on each hand-held dynamometer plus the KinCom for peak force (kg)

Intra-rater reliability		Assessor-A		Assessor-B		KinCom
		Lafayette	Hoggan	Lafayette	Hoggan	
ADF	Day 1 – Mean (SD)	19.19 (4.92)	20.89 (3.64)	27.47 (5.96)	30.68 (6.89)	18.47 (6.87)
	Day 2 – Mean (SD)	17.83 (4.35)	20.92 (4.11)	27.42 (5.85)	29.93 (5.49)	17.52 (6.30)
	ICC (95% CI)	0.89 (0.76,0.95)	0.87 (0.71,0.94)	0.88 (0.75,0.95)	0.87 (0.71,0.94)	0.78 (0.43,0.92)
	SEM (%)	8.62	6.20	7.39	8.13	17.45
	MDC (%)	23.89	17.19	20.47	22.52	48.36
APF	Day 1 – Mean (SD)	51.00 (10.94)	48.06 (8.12)	52.29 (11.17)	51.16 (10.85)	91.02 (35.94)
	Day 2 – Mean (SD)	50.42 (11.34)	47.83 (9.70)	51.95 (10.05)	51.30 (11.27)	83.16 (36.13)
	ICC (95% CI)	0.84 (0.66,0.93)	0.87 (0.70,0.95)	0.87 (0.72,0.94)	0.74 (0.38,0.89)	0.98 (0.95,0.99)
	SEM (%)	8.53	6.06	7.70	10.81	5.72
	MDC (%)	23.64	16.81	21.35	29.97	15.86
HAB	Day 1 – Mean (SD)	13.85 (3.73)	13.23 (3.91)	13.06 (3.03)	13.38 (3.83)	11.91 (3.39)
	Day 2 – Mean (SD)	13.01 (3.27)	12.77 (3.50)	12.46 (3.71	12.94 (3.74)	11.14 (3.45)
	ICC (95% CI)	0.87 (0.73,0.94)	0.94 (0.86,0.97)	0.92 (0.84,0.96)	0.95 (0.89,0.98)	0.95 (0.88,0.98)
	SEM (%)	9.59	7.30	6.43	6.53	6.17
	MDC (%)	26.59	20.23	17.82	18.11	17.10
HAD	Day 1 – Mean (SD)	18.27 (6.31)	17.53 (5.81)	19.65 (6.91)	20.37 (7.27)	19.56 (5.91)
	Day 2 – Mean (SD)	18.57 (6.27)	18.16 (5.84)	19.10 (7.45)	19.56 (6.99)	18.92 (6.81)
	ICC (95% CI)	0.96 (0.92,0.98)	0.97 (0.92,0.99)	0.97 (0.93,0.99)	0.97 (0.92,0.99)	0.98 (0.94,0.99)
	SEM (%)	6.82	5.74	6.09	6.68	4.48
	MDC (%)	18.89	15.91	16.87	18.51	12.42
HE	Day 1 – Mean (SD)	23.01 (5.34)	23.60 (5.69)	25.25 (6.80)	24.41 (5.66)	25.82 (6.58)
	Day 2 – Mean (SD)	23.45 (6.62)	23.34 (5.92)	25.16 (6.67)	24.31 (5.97)	25.43 (7.13)
	ICC (95% CI)	0.92 (0.82,0.96)	0.95 (0.90,0.98)	0.94 (0.86,0.97)	0.95 (0.88,0.98)	0.92 (0.81,0.97)
	SEM (%)	6.77	5.22	6.76	5.34	7.03
	MDC (%)	18.76	14.48	18.74	14.79	19.49

HF	Day 1 – Mean (SD)	30.44 (7.84)	31.23 (7.82)	36.54 (8.23)	38.63 (8.26)	34.83 (10.48)
	Day 2 – Mean (SD)	30.05 (6.53)	31.72 (7.81)	36.62 (6.74)	36.53 (7.50)	35.86 (9.73)
	ICC (95% CI)	0.94 (0.88,0.97)	0.95 (0.89,0.98)	0.93 (0.86,0.97)	0.85 (0.67,0.94)	0.95 (0.89,0.98)
	SEM (%)	6.15	5.43	5.83	8.17	6.45
	MDC (%)	17.05	15.05	16.16	22.65	17.89
KE	Day 1 – Mean (SD)	44.27 (11.34)	50.41 (13.89)	43.92 (13.62)	47.70 (13.03)	63.54 (23.76)
	Day 2 – Mean (SD)	41.51 (11.55)	46.07 (12.49)	42.66 (13.52)	46.13 (13.86)	58.66 (25.19)
	ICC (95% CI)	0.91 (0.80,0.96)	0.90 (0.76,0.96)	0.92 (0.83,0.96)	0.89 (0.76,0.95)	0.98 (0.94,0.99)
	SEM (%)	7.73	8.54	8.72	8.98	5.67
	MDC (%)	21.42	23.67	24.16	24.88	15.72
KF	Day 1 – Mean (SD)	23.28 (5.74)	23.58 (6.19)	27.55 (9.15)	29.46 (7.69)	25.84 (7.28)
	Day 2 – Mean (SD)	23.19 (5.25)	23.99 (4.84)	27.49 (7.90)	28.67 (7.45)	25.73 (7.35)
	ICC (95% CI)	0.92 (0.83,0.96)	0.89 (0.71,0.96)	0.94 (0.87,0.97)	0.96 (0.90,0.98)	0.94 (0.86,0.98)
	SEM (%)	6.93	8.59	8.07	5.29	6.67
	MDC (%)	19.21	23.81	22.36	14.66	18.48

Note: ADF = ankle dorsiflexors; APF = ankle plantarflexors; HAB = hip abductors; HAD = hip adductors; HE = hip extensors; HF = hip flexors; KE = knee extensors; KF = knee flexors; SD = standard deviation; ICC = intraclass correlation coefficient; CI = confidence intervals; SEM = standard error of measurement (expressed as percentage of the mean); MDC = minimal detectable change with 95% confidence intervals (expressed as a percentage of the mean). Table adapted with permission from Mentiplay et al. (2015b).

Table 4.3. Mean, standard deviation and intra-rater reliability for each assessor on each hand-held dynamometer plus the KinCom for rate of force development (kg/s)

Intra-rater reliability		Assessor-A		Assessor-B		KinCom
		Lafayette	Hoggan	Lafayette	Hoggan	
ADF	Day 1 – Mean (SD)	35.55 (11.38)	46.17 (12.51)	53.06 (14.63)	71.28 (18.92)	67.74 (28.40)
	Day 2 – Mean (SD)	32.90 (10.27)	45.46 (13.73)	53.34 (17.96)	68.26 (19.70)	64.59 (25.61)
	ICC (95% CI)	0.87 (0.72,0.94)	0.84 (0.63,0.93)	0.49 (-0.10,0.76)	0.75 (0.44,0.88)	0.77 (0.40,0.91)
	SEM (%)	11.63	11.01	19.69	13.38	20.24
	MDC (%)	32.24	30.52	54.57	37.09	56.10
APF	Day 1 – Mean (SD)	111.31 (35.70)	125.40 (35.58)	118.54 (38.41)	144.89 (40.28)	230.81 (113.89)
	Day 2 – Mean (SD)	107.63 (27.01)	119.24 (35.82)	113.41 (27.76)	143.09 (41.15)	216.40 (111.54)
	ICC (95% CI)	0.89 (0.76,0.95)	0.81 (0.55,0.92)	0.85 (0.67,0.93)	0.81 (0.56,0.92)	0.95 (0.88,0.98)
	SEM (%)	10.64	12.37	12.68	12.05	10.81
	MDC (%)	29.48	34.28	35.14	33.41	29.96
HAB	Day 1 – Mean (SD)	30.49 (10.01)	34.80 (13.56)	30.08 (9.19)	37.78 (15.86)	37.75 (15.12)
	Day 2 – Mean (SD)	28.80 (7.54)	33.51 (9.30)	29.16 (8.30)	36.71 (13.45)	34.35 (13.64)
	ICC (95% CI)	0.84 (0.66,0.93)	0.90 (0.77,0.95)	0.74 (0.44,0.88)	0.89 (0.76,0.95)	0.88 (0.71,0.95)
	SEM (%)	13.08	12.50	15.69	13.92	13.65
	MDC (%)	36.27	34.65	43.49	38.59	37.83
HAD	Day 1 – Mean (SD)	39.97 (17.13)	43.42 (19.90)	44.73 (19.67)	58.55 (27.95)	58.23 (24.36)
	Day 2 – Mean (SD)	39.33 (13.02)	46.55 (14.52)	43.54 (16.15)	55.74 (22.40)	54.76 (27.89)
	ICC (95% CI)	0.91 (0.80,0.96)	0.87 (0.64,0.95)	0.93 (0.84,0.97)	0.94 (0.86,0.98)	0.92 (0.78,0.97)
	SEM (%)	13.00	16.85	11.96	11.69	12.13
	MDC (%)	36.04	46.69	33.15	32.40	33.61
HE	Day 1 – Mean (SD)	47.42 (15.08)	56.88 (20.79)	58.21 (17.55)	72.18 (25.61)	83.10 (29.19)
	Day 2 – Mean (SD)	48.26 (14.57)	56.31 (14.84)	55.82 (15.43)	67.79 (17.93)	84.39 (28.50)
	ICC (95% CI)	0.91 (0.80,0.96)	0.86 (0.69,0.94)	0.87 (0.73,0.94)	0.89 (0.74,0.95)	0.87 (0.68,0.95)
	SEM (%)	9.70	13.58	10.71	11.82	12.62
	MDC (%)	26.88	37.64	29.67	32.77	34.98

HF	Day 1 – Mean (SD)	67.45 (18.88)	88.05 (23.72)	84.78 (23.54)	112.95 (30.30)	147.38 (46.94)
	Day 2 – Mean (SD)	65.82 (17.32)	89.84 (22.51)	82.34 (18.84)	104.49 (28.15)	152.80 (54.08)
	ICC (95% CI)	0.88 (0.75,0.94)	0.86 (0.66,0.94)	0.82 (0.62,0.92)	0.87 (0.71,0.95)	0.94 (0.85,0.98)
	SEM (%)	9.65	10.26	11.68	9.52	7.87
	MDC (%)	26.76	28.43	32.38	26.39	21.80
KE	Day 1 – Mean (SD)	83.24 (27.78)	126.25 (55.88)	87.65 (24.45)	125.37 (43.44)	210.61 (91.22)
	Day 2 – Mean (SD)	82.36 (27.09)	106.23 (34.03)	80.38 (25.90)	112.72 (36.38)	200.01 (86.90)
	ICC (95% CI)	0.84 (0.66,0.93)	0.71 (0.26,0.88)	0.71 (0.37,0.87)	0.77 (0.50,0.90)	0.98 (0.95,0.99)
	SEM (%)	13.18	24.04	15.02	16.55	5.81
	MDC (%)	36.54	66.63	41.64	45.86	16.11
KF	Day 1 – Mean (SD)	42.87 (16.77)	52.07 (17.22)	53.92 (24.01)	77.15 (27.58)	90.55 (28.42)
	Day 2 – Mean (SD)	38.86 (13.53)	49.83 (16.10)	52.47 (15.47)	70.63 (20.90)	92.74 (36.16)
	ICC (95% CI)	0.91 (0.80,0.96)	0.78 (0.38,0.92)	0.85 (0.69,0.93)	0.83 (0.56,0.94)	0.93 (0.82,0.97)
	SEM (%)	11.99	15.65	17.02	14.69	8.48
	MDC (%)	33.24	43.38	47.17	40.73	23.51

Note: ADF = ankle dorsiflexors; APF = ankle plantarflexors; HAB = hip abductors; HAD = hip adductors; HE = hip extensors; HF = hip flexors; KE = knee extensors; KF = knee flexors; SD = standard deviation; ICC = intraclass correlation coefficient; CI = confidence intervals; SEM = standard error of measurement (expressed as percentage of the mean); MDC = minimal detectable change with 95% confidence intervals (expressed as a percentage of the mean). Table adapted with permission from Mentiplay et al. (2015b).

Inter-rater reliability results, comparing the two assessors, are presented in Table 4.4. The inter-rater reliability was good to excellent (ICC $\geq$ 0.75) for measures of peak force and RFD in all muscle groups except for peak force of the ankle dorsiflexors (ICC = 0.68) and ankle plantarflexors (ICC = 0.66) with the Hoggan HHD, and RFD of the ankle dorsiflexors (ICC = 0.70) with the Lafayette HHD.

Table 4.4 presents the results from the inter-device analysis, comparing results between the two HHDs. Inter-device reliability demonstrated good to excellent correlations ($r \geq 0.75$) between the Lafayette and Hoggan HHDs for all peak force measures. Concordance correlations for peak force also showed good to excellent agreement ($R_c \geq 0.75$) with the exception of ankle dorsiflexors by Assessor-A ($R_c = 0.66$). Inter-device analysis of RFD measures showed good to excellent correlations ($r \geq 0.75$) for all muscle groups with the exception of the ankle dorsiflexors by Assessor-B ($r = 0.73$) and the knee extensors for Assessor-A and Assessor-B ($r = 0.41, 0.57$ respectively). The majority of RFD concordance correlation results showed moderate to excellent agreement (Table 4.4). Measures of RFD for the knee extensors showed poor agreement and moderate correlations between devices for both assessors.

Table 4.4. Inter-rater and inter-device reliability for the hand-held dynamometers

		Inter-rater reliability				Inter-device reliability			
		Peak force (kg)		RFD (kg/s)		Peak force (kg)		RFD (kg/s)	
		Lafayette	Hoggan	Lafayette	Hoggan	Assessor-A	Assessor-B	Assessor-A	Assessor-B
ADF	ICC (95% CI)	0.77 (0.50,0.89)	0.68 (0.29,0.86)	0.70 (0.36,0.86)	0.75 (0.44,0.89)				
	SEM (%)	11.30	11.54	16.05	13.41				
	MDC (%)	22.15	22.63	31.46	26.28				
	R (95% CI)	0.59 (0.29,0.79)	0.61 (0.29,0.81)	0.52 (0.19,0.74)	0.68 (0.40,0.84)	0.79 (0.59,0.90)	0.84 (0.68,0.92)	0.85 (0.70,0.93)	0.73 (0.49,0.87)
	R_c (95% CI)	0.25 (0.09,0.40)	0.19 (0.06,0.32)	0.24 (0.06,0.41)	0.26 (0.10,0.40)	0.66 (0.44,0.81)	0.76 (0.57,0.87)	0.53 (0.34,0.68)	0.44 (0.23,0.61)
APF	ICC (95% CI)	0.81 (0.60,0.91)	0.66 (0.24,0.85)	0.90 (0.79,0.95)	0.83 (0.61,0.92)				
	SEM (%)	9.33	11.18	10.25	11.74				
	MDC (%)	18.29	21.91	20.08	23.01				
	R (95% CI)	0.66 (0.39,0.83)	0.47 (0.10,0.73)	0.78 (0.58,0.89)	0.71 (0.45,0.86)	0.85 (0.70,0.93)	0.75 (0.52,0.88)	0.86 (0.71,0.93)	0.78 (0.57,0.89)
	R_c (95% CI)	0.66 (0.40,0.83)	0.44 (0.10,0.69)	0.77 (0.56,0.88)	0.66 (0.40,0.82)	0.80 (0.64,0.89)	0.75 (0.52,0.88)	0.74 (0.55,0.85)	0.61 (0.39,0.77)
HAB	ICC (95% CI)	0.92 (0.84,0.96)	0.95 (0.89,0.98)	0.92 (0.82,0.96)	0.88 (0.73,0.94)				
	SEM (%)	6.92	6.51	9.24	14.27				
	MDC (%)	13.56	12.75	18.10	27.97				
	R (95% CI)	0.89 (0.78,0.95)	0.91 (0.81,0.96)	0.85 (0.71,0.93)	0.80 (0.61,0.90)	0.96 (0.92,0.98)	0.92 (0.83,0.96)	0.90 (0.79,0.95)	0.84 (0.69,0.92)
	R_c (95% CI)	0.84 (0.71,0.91)	0.91 (0.82,0.96)	0.85 (0.71,0.92)	0.78 (0.59,0.88)	0.96 (0.91,0.98)	0.89 (0.81,0.94)	0.80 (0.65,0.88)	0.64 (0.47,0.77)
HAD	ICC (95% CI)	0.98 (0.96,0.99)	0.95 (0.88,0.98)	0.92 (0.82,0.96)	0.91 (0.79,0.96)				
	SEM (%)	4.54	7.72	12.59	14.00				
	MDC (%)	8.90	15.12	24.68	27.44				
	R (95% CI)	0.96 (0.92,0.98)	0.92 (0.82,0.97)	0.82 (0.64,0.91)	0.84 (0.66,0.93)	0.95 (0.89,0.98)	0.96 (0.91,0.98)	0.84 (0.66,0.93)	0.91 (0.81,0.96)
	R_c (95% CI)	0.94 (0.88,0.97)	0.86 (0.73,0.93)	0.77 (0.59,0.88)	0.71 (0.50,0.84)	0.95 (0.88,0.98)	0.96 (0.91,0.98)	0.71 (0.53,0.83)	0.73 (0.56,0.84)
HE	ICC (95% CI)	0.92 (0.82,0.96)	0.95 (0.89,0.98)	0.89 (0.77,0.95)	0.86 (0.70,0.94)				
	SEM (%)	7.29	5.34	10.15	13.36				
	MDC (%)	14.29	10.46	19.90	26.18				
	R (95% CI)	0.87 (0.74,0.94)	0.90 (0.79,0.95)	0.83 (0.67,0.92)	0.79 (0.59,0.90)	0.96 (0.92,0.98)	0.93 (0.85,0.97)	0.77 (0.56,0.89)	0.89 (0.77,0.95)
	R_c (95% CI)	0.78 (0.63,0.88)	0.89 (0.77,0.95)	0.64 (0.44,0.78)	0.61 (0.39,0.76)	0.95 (0.89,0.98)	0.89 (0.79,0.94)	0.64 (0.42,0.78)	0.70 (0.52,0.82)

HF	ICC (95% CI)	0.93 (0.85,0.97)	0.92 (0.80,0.96)	0.85 (0.69,0.93)	0.87 (0.69,0.94)				
	SEM (%)	6.39	6.71	10.76	9.80				
	MDC (%)	12.53	13.15	21.08	19.21				
	R (95% CI)	0.86 (0.73,0.93)	0.84 (0.66,0.93)	0.83 (0.67,0.92)	0.75 (0.49,0.89)	0.91 (0.80,0.96)	0.82 (0.64,0.91)	0.85 (0.69,0.93)	0.81 (0.62,0.91)
	R_c (95% CI)	0.69 (0.50,0.81)	0.63 (0.41,0.79)	0.61 (0.42,0.75)	0.57 (0.32,0.75)	0.91 (0.81,0.96)	0.81 (0.62,0.91)	0.54 (0.34,0.69)	0.56 (0.35,0.71)
KE	ICC (95% CI)	0.89 (0.77,0.95)	0.90 (0.77,0.96)	0.80 (0.56,0.91)	0.75 (0.44,0.89)				
	SEM (%)	9.30	8.76	13.84	19.58				
	MDC (%)	18.23	17.18	27.12	38.37				
	R (95% CI)	0.86 (0.71,0.93)	0.82 (0.63,0.92)	0.61 (0.31,0.80)	0.56 (0.21,0.78)	0.93 (0.85,0.97)	0.89 (0.77,0.95)	0.41 (0.02,0.69)	0.57 (0.25,0.78)
	R_c (95% CI)	0.84 (0.70,0.92)	0.81 (0.62,0.91)	0.60 (0.30,0.79)	0.54 (0.22,0.75)	0.83 (0.70,0.91)	0.85 (0.72,0.93)	0.24 (0.02,0.44)	0.31 (0.11,0.49)
KF	ICC (95% CI)	0.82 (0.62,0.91)	0.92 (0.77,0.97)	0.81 (0.60,0.91)	0.82 (0.49,0.94)				
	SEM (%)	12.53	7.40	18.46	14.71				
	MDC (%)	24.56	14.51	36.18	28.83				
	R (95% CI)	0.78 (0.58,0.89)	0.84 (0.59,0.94)	0.69 (0.44,0.84)	0.71 (0.33.0.89)	0.95 (0.88,0.98)	0.85 (0.68,0.93)	0.90 (0.76,0.96)	0.88 (0.74,0.95)
	R_c (95% CI)	0.61 (0.41,0.76)	0.70 (0.39,0.87)	0.55 (0.32,0.72)	0.43 (0.13,0.65)	0.94 (0.85,0.97)	0.84 (0.67,0.92)	0.78 (0.58,0.89)	0.66 (0.46,0.80)

Note: ADF = ankle dorsiflexors; APF = ankle plantarflexors; HAB = hip abductors; HAD = hip adductors; HE = hip extensors; HF = hip flexors; KE = knee extensors; KF = knee flexors; ICC = intraclass correlation coefficient; CI = confidence intervals; SEM = standard error of measurement (expressed as percentage of the mean); MDC = minimal detectable change with 95% confidence intervals (expressed as a percentage of the mean); R = Pearson's correlation coefficient; R_c = concordance correlation coefficient. Table adapted with permission from Mentiplay et al. (2015b).

4.4.3 Concurrent validity of HHDs

Table 4.5 presents the results from the concurrent validity analysis for peak force and RFD measures, comparing the results from the HHDs to the KinCom dynamometer. Validity of peak force measures were good to excellent (ICC $\geq$ 0.75) with exception of most ankle results which demonstrated moderate validity; this included ankle dorsiflexors by Assessor-A on the Lafayette HHD (ICC = 0.62) and the Hoggan HHD (ICC = 0.51) and ankle plantarflexors by Assessor-A and Assessor-B on the Lafayette HHD (ICC = 0.51, 0.54 respectively) and the Hoggan HHD (ICC = 0.47, 0.40 respectively). The validity of RFD measures was mixed, however all measures of the hip muscle groups demonstrated good to excellent validity (ICC $\geq$ 0.75) except for the hip abductors by Assessor-B on the Lafayette HHD (ICC = 0.74). Ankle and knee RFD measures displayed mostly moderate to good validity. Results from the Bland-Altman plots are presented in the appendices (Appendix B).

Table 4.5. Validity of peak force and rate of force development measures of the hand-held dynamometers compared to the KinCom

	Validity	Peak force (kg)				RFD (kg/s)			
		Assessor-A		Assessor-B		Assessor-A		Assessor-B	
		Lafayette	Hoggan	Lafayette	Hoggan	Lafayette	Hoggan	Lafayette	Hoggan
ADF	ICC (95% CI)	0.62 (0.15,0.83)	0.61 (0.09,0.83)	0.79 (0.52,0.91)	0.76 (0.44,0.90)	0.41 (-0.32,0.74)	0.40 (-0.36,0.74)	0.31 (-0.56,0.70)	0.72 (0.35,0.88)
	R (95% CI)	0.46 (0.09,0.72)	0.49 (0.11,0.75)	0.66 (0.36,0.84)	0.61 (0.28,0.81)	0.35 (-0.04,0.65)	0.34 (-0.06,0.65)	0.23 (-0.18,0.57)	0.60 (0.27,0.80)
	R_c (95% CI)	0.44 (0.10,0.70)	0.39 (0.09,0.63)	0.30 (0.11,0.46)	0.22 (0.06,0.36)	0.11 (-0.02,0.24)	0.17 (-0.04,0.36)	0.16 (-0.12,0.41)	0.54 (0.24,0.75)
APF	ICC (95% CI)	0.51 (-0.12,0.78)	0.47 (-0.25,0.78)	0.54 (-0.14,0.81)	0.40 (-0.42,0.74)	0.73 (0.38,0.88)	0.70 (0.31,0.87)	0.70 (0.32,0.87)	0.54 (-0.06,0.80)
	R (95% CI)	0.49 (0.12,0.74)	0.59 (0.24,0.81)	0.51 (0.14,0.75)	0.41 (0.00,0.70)	0.73 (0.47,0.87)	0.69 (0.40,0.86)	0.67 (0.37,0.84)	0.44 (0.05,0.72)
	R_c (95% CI)	0.16 (0.02,0.30)	0.13 (0.03,0.23)	0.17 (0.03,0.30)	0.11 (-0.01,0.22)	0.24 (0.10,0.38)	0.30 (0.12,0.46)	0.25 (0.09,0.39)	0.23 (0.01,0.43)
HAB	ICC (95% CI)	0.88 (0.74,0.95)	0.89 (0.75,0.95)	0.91 (0.80,0.96)	0.91 (0.79,0.96)	0.82 (0.60,0.92)	0.82 (0.59,0.92)	0.74 (0.42,0.88)	0.88 (0.74,0.95)
	R (95% CI)	0.79 (0.58,0.90)	0.80 (0.59,0.91)	0.85 (0.69,0.93)	0.83 (0.65,0.92)	0.76 (0.53,0.89)	0.70 (0.42,0.86)	0.66 (0.37,0.83)	0.79 (0.58,0.90)
	R_c (95% CI)	0.66 (0.43,0.81)	0.75 (0.52,0.88)	0.80 (0.63,0.90)	0.77 (0.57,0.89)	0.63 (0.40,0.78)	0.70 (0.43,0.85)	0.52 (0.26,0.70)	0.79 (0.59,0.90)
HAD	ICC (95% CI)	0.95 (0.87,0.98)	0.94 (0.84,0.98)	0.95 (0.89,0.98)	0.94 (0.85,0.98)	0.86 (0.68,0.94)	0.92 (0.80,0.97)	0.92 (0.82,0.97)	0.94 (0.87,0.98)
	R (95% CI)	0.90 (0.78,0.96)	0.90 (0.76,0.96)	0.91 (0.80,0.96)	0.89 (0.75,0.95)	0.82 (0.62,0.92)	0.87 (0.70,0.95)	0.88 (0.74,0.95)	0.90 (0.78,0.96)
	R_c (95% CI)	0.89 (0.76,0.95)	0.85 (0.67,0.93)	0.91 (0.80,0.96)	0.89 (0.76,0.95)	0.58 (0.36,0.74)	0.79 (0.57,0.90)	0.74 (0.55,0.86)	0.89 (0.76,0.95)
HE	ICC (95% CI)	0.88 (0.72,0.95)	0.90 (0.76,0.95)	0.94 (0.85,0.97)	0.93 (0.85,0.97)	0.76 (0.46,0.90)	0.88 (0.73,0.95)	0.87 (0.69,0.94)	0.88 (0.72,0.95)
	R (95% CI)	0.80 (0.59,0.91)	0.82 (0.62,0.92)	0.88 (0.74,0.95)	0.89 (0.76,0.95)	0.76 (0.52,0.89)	0.84 (0.67,0.93)	0.83 (0.65,0.92)	0.80 (0.59,0.91)
	R_c (95% CI)	0.72 (0.49,0.85)	0.77 (0.57,0.89)	0.88 (0.74,0.94)	0.86 (0.71,0.93)	0.28 (0.13,0.42)	0.52 (0.32,0.68)	0.52 (0.31,0.67)	0.74 (0.51,0.87)
HF	ICC (95% CI)	0.94 (0.87,0.97)	0.94 (0.85,0.97)	0.94 (0.86,0.97)	0.92 (0.82,0.97)	0.77 (0.50,0.90)	0.78 (0.49,0.91)	0.80 (0.56,0.91)	0.92 (0.82,0.97)
	R (95% CI)	0.92 (0.83,0.96)	0.90 (0.77,0.96)	0.90 (0.79,0.95)	0.88 (0.74,0.95)	0.88 (0.75,0.95)	0.77 (0.53,0.90)	0.79 (0.58,0.90)	0.95 (0.89,0.98)
	R_c (95% CI)	0.80 (0.65,0.89)	0.84 (0.68,0.92)	0.87 (0.76,0.93)	0.81 (0.64,0.91)	0.19 (0.09,0.28)	0.30 (0.13,0.45)	0.28 (0.14,0.42)	0.61 (0.44,0.74)

KE	ICC (95% CI)	0.82 (0.58,0.92)	0.90 (0.76,0.96)	0.92 (0.82,0.97)	0.88 (0.72,0.95)	0.40 (-0.37,0.74)	0.82 (0.58,0.92)	0.63 (0.16,0.84)	0.67 (0.24,0.85)
	R (95% CI)	0.82 (0.63,0.92)	0.87 (0.71,0.94)	0.90 (0.78,0.96)	0.86 (0.70,0.94)	0.36 (-0.04,0.66)	0.72 (0.45,0.87)	0.68 (0.39,0.85)	0.57 (0.23,0.79)
	R_c (95% CI)	0.48 (0.28,0.64)	0.71 (0.51,0.84)	0.61 (0.42,0.75)	0.62 (0.42,0.77)	0.07 (-0.01,0.15)	0.38 (0.17,0.56)	0.13 (0.04,0.22)	0.25 (0.07,0.41)
KF	ICC (95% CI)	0.80 (0.55,0.91)	0.79 (0.39,0.93)	0.85 (0.67,0.93)	0.87 (0.66,0.95)	0.72 (0.38,0.88)	0.79 (0.41,0.92)	0.84 (0.64,0.93)	0.84 (0.60,0.93)
	R (95% CI)	0.68 (0.40,0.84)	0.66 (0.25,0.87)	0.76 (0.53,0.89)	0.76 (0.48,0.90)	0.65 (0.35,0.83)	0.73 (0.39,0.90)	0.73 (0.48,0.87)	0.72 (0.42,0.88)
	R_c (95% CI)	0.64 (0.37,0.81)	0.65 (0.25,0.86)	0.72 (0.49,0.85)	0.73 (0.44,0.88)	0.18 (0.06,0.30)	0.29 (0.09,0.48)	0.36 (0.17,0.52)	0.58 (0.29,0.77)

Note: ADF = ankle dorsiflexors; APF = ankle plantarflexors; HAB = hip abductors; HAD = hip adductors; HE = hip extensors; HF = hip flexors; KE = knee extensors; KF = knee flexors; ICC = intraclass correlation coefficient; CI = confidence intervals; R = Pearson's correlation coefficient; R_c = concordance correlation coefficient. Table adapted with permission from Mentiplay et al. (2015b).

4.5 Discussion

Hand-held dynamometry demonstrated good to excellent intra-rater and inter-rater reliability for the assessment of isometric lower limb muscle strength and power in a healthy and unimpaired cohort. Comparison of the HHDs to a laboratory-based dynamometer showed moderate to excellent concurrent validity for both measures of isometric strength and power. To date, this is the first study to evaluate these psychometric properties when assessing isometric muscle strength in all major muscle groups of the lower limbs with a greater than poor sample size based on the COSMIN checklist (Terwee et al., 2012). It is also the first to report the use of HHDs to assess isometric muscle power. These low cost, portable and easy-to-use devices have shown potential for use as clinically feasible alternatives to laboratory-based dynamometry for isometric strength measures in the current and previous studies. The results from the current study also indicate promise for HHDs in the assessment of isometric muscle power.

Prior research has focussed primarily on the assessment and treatment of muscle strength in various clinical populations including neurological populations (Williams et al., 2014b); however, muscle power is another important consideration. Initial evidence has shown that RFD may have a stronger association with gait velocity than muscle strength post-stroke (Pohl et al., 2002). Knowledge of both muscle strength and power may be of use to clinicians when assessing and treating their patients, as they provide complementary information on muscle performance. The results for both peak force and RFD can be obtained from the same trial using the same methodology, adding to the clinical feasibility of HHDs for patient assessment. A potential limitation of widespread RFD assessment is a lack of software to calculate RFD results. For this reason, a freely available software program has been created (by thesis author BFM) (available at http://www.rehabtools.org) which allows the user to

obtain the 200ms rolling window RFD measures from data stored on a Lafayette HHD. A software program to analyse data from a Hoggan HHD is not available due to the additional cost of purchasing the data recording software for this device and the issues experienced when saving recorded data during testing sessions.

Inter-rater reliability results were good to excellent for peak force and RFD measures using the Lafayette and Hoggan HHDs. However, agreement between the assessors ranged from moderate to excellent for both measures of strength and RFD, indicating that although results between assessors are comparable, the exact result may not be interchangeable. Previous research examining inter-rater reliability of HHDs for the assessment of isometric strength has found mixed results (Bandinelli et al., 1999; Bohannon, 2012; Malliaras, Hogan, Nawrocki, Crossley, & Schache, 2009; Poulsen et al., 2012; Richardson, Stratford, & Cripps, 1998; Vanpee et al., 2011). One prior study examined the inter-rater reliability between male and female assessors with varying levels of experience and found acceptable inter-rater reliability regardless of assessor characteristics or experience (Kelln et al., 2008). Previous studies have commented on the influence that assessor strength may have on HHD testing (Bohannon, 2012; Wikholm & Bohannon, 1991). Following the experience of performing this study, it was deemed that sufficient strength levels are required to control the movement of the person being tested, after which the technique of the assessor is likely to be just as important for obtaining valid results. During testing, it is recommended that assessors have a wide base of support, use their own body mass to lean into the participant and keep arms tucked in towards their body.

On closer inspection of the results from each lower limb muscle group, assessment of the hip musculature showed the strongest reliability and validity for both measures of isometric strength and power. Previous research examining the reliability and validity of HHDs for

assessment of hip strength has found similar results in a range of populations (Arnold, Warkentin, Chilibeck, & Magnus, 2010; Bohannon, 1986b; Fulcher, Hanna, & Raina Elley, 2010; Taylor, Dodd, & Graham, 2004; Thorborg et al., 2010). Assessment of knee strength demonstrated good to excellent reliability and validity, with the exception of the validity of RFD measures of the knee extensors which ranged from moderate to excellent. This may be due to the higher levels of force and power generated in the knee extensors, leading to difficulty by the assessors in stabilising the HHD during the initial rise in force and thus impacting on the measurement of RFD. Therefore, if knee extension RFD is the primary measure of interest, it may be pertinent to consider external bracing during assessment.

Assessment of the ankle muscle groups demonstrated good to excellent reliability, however validity was lower than expected. Similar to the current study, previous research in a healthy population has also shown poor validity of HHD measures of plantarflexor strength compared to a fixed KinCom dynamometer (Marmon et al., 2013). Assessment of the ankle muscle groups is important as the plantarflexors have a primary role in power generation during walking (Winter, 1983) and the dorsiflexors have been reported to be the lower body muscle group most strongly associated with gait velocity post-stroke (as shown in Study One) (Mentiplay et al., 2015a). The mixed validity results in the current study and previous research (Marmon et al., 2013) may be due to the ankle plantar/dorsiflexor attachment used on the KinCom. During testing, participants reported difficulty when using the attachment, especially for ankle dorsiflexion, due to the lack of stabilisation that the attachment provides. The ankle dorsiflexors also showed larger SEM and MDC values for the KinCom compared with the HHDs indicating greater variability. The ankle attachment for the KinCom does not fit tightly within the load cell, which may have resulted in measurement error which was shown with the higher SEM and MDC values. Similar comments about the ankle attachment

have been made by previous studies when assessing ankle muscle strength using the KinCom (Kaminski, Perrin, Mattacola, Szczerba, & Bernier, 1995).

Analysis of the SEM for intra-rater reliability showed small percentages of the mean, indicating low measurement error. The RFD showed higher SEM compared to peak force values (< 10% for peak force, except one measure; < 20% for RFD, except one measure). The MDC results were also higher for RFD measures compared to peak force (< 25% for peak force, except two measures; < 50% for RFD, except two measures). This indicates that caution is needed when measuring RFD from HHD in healthy populations as a large change in RFD is required to be confident of a true change in RFD levels. However, analysis of the SEM and MDC for HHD measures of isometric strength and power may prove more informative in clinical populations than the healthy participants used in the current study, to provide population specific results.

Measurement of RFD has been used widely in the previous literature, although there is a lack of consensus as to which method is the most appropriate. After a comparison of various techniques for assessing RFD that were applicable to HHD, this study utilised a peak 200ms iterative windowed time period method to determine peak RFD. This study did not use methods that involve determining the onset of contraction, as previous work has commented on the arbitrary nature of determining contraction onset for RFD calculation (Pua, Wrigley, Cowan, & Bennell, 2008). Instead RFD was identified using algorithms that scan the entire trial from the first sample recorded. This method ignores any potential erroneous recordings obtained by placing the HHD on the lower limb, as the peak RFD across the trial does not occur during this initial placement. A longer time window than the 200ms used in this study may produce higher reliability results (as a longer time window would provide more measurement stability between trials), however longer time windows may include unwanted

plateaus that do not reflect the ability to produce force quickly. We found the 200ms successive time window analysis technique to be robust to different sources of error during testing, however further research is needed in clinical populations to verify the findings of the current study.

Comparison between the two HHDs used in this study revealed no apparent differences in the reliability or validity for either variable of isometric strength or power. The inter-device reliability suggests that peak force results are interchangeable between the two different HHDs (e.g. 20Nm on the Lafayette HHD corresponds to 20Nm on the Hoggan HHD), however caution is necessary if interchanging RFD results between devices with the mixed agreement shown in this study. Additionally, both HHDs demonstrated mixed agreement with the KinCom for both strength and RFD. This lack of agreement between the three devices, especially for RFD, may be due to the different sampling rates employed by each device. The recommended sampling rate for RFD calculation is at least 1000Hz (Maffiuletti et al., 2016), with the two HHDs sampling much lower than 1000Hz. As such, the HHD data was resampled to 1000Hz for the HHDs to provide an unbiased comparison, although the lower sampling rates of the HHDs need to considered and may have resulted in the lack of agreement between the devices. Based on the reliability and validity results of the current study, there can be no recommendation as to which HHD should be used in future testing as both HHDs displayed similar reliability and validity. In terms of the feasibility of assessment, the Lafayette HHD was easier to use due to the memory within the device which allowed for the raw data to be downloaded following testing. The Hoggan HHD needed to be wirelessly connected to a computer during testing for assessment of the raw data, which may limit the clinical feasibility of this device. The software package for the Hoggan HHD occasionally lost recorded data during collection for reasons unknown to the authors, further limiting the feasibility of the Hoggan HHD. A consideration for the future development of

HHDs is the real-time calculation and display of RFD. Currently, the calculation of RFD from HHDs requires post-testing analysis that may preclude the use of RFD in a clinical setting.

4.5.1 Limitations

The cohort used in this study was young, healthy, unimpaired and physically active individuals. Even with the assessors bracing against a wall, the assessment of the knee extensors and ankle plantarflexors was unable to be completed for one male participant. These two muscle groups recorded much higher strength and power values on the fixed KinCom dynamometer across all participants. It is likely that the assessment of strength and RFD would be easier when assessing those individuals with muscle weakness, such as the elderly or those with neurological impairment. The findings from this study may thus not be generalisable to some clinical populations. A recent review demonstrated that the reliability of HHDs for isometric strength assessment is generally higher in clinical populations compared with healthy participants (Bohannon, 2012), highlighting the need for population specific assessment of the psychometric properties of HHD. The lower reliability in healthy cohorts could be for a number of reasons including difficulties when testing stronger participants or the lower between-subject variability in healthy populations compared to the clinical populations. The inclusion of a healthy cohort was required in this study due to the large time and effort demands of the testing sessions (e.g. participants performed 80 MVCs per session). Further research is needed to examine the psychometric properties of HHD for assessments of isometric strength and RFD in clinical populations. Nonetheless, the inclusion of healthy participants does not discount the importance of our study, as normative data are required, albeit not normalised, to allow comparison with other populations and thus establishing reliability and validity in this group was considered essential.

The use of the KinCom as the criterion reference or 'gold standard' device may be seen as a limitation of this study. The results showed lower than expected validity for the ankle muscle groups when comparing the HHD with the values obtained using the KinCom. The ankle attachment used in the study, as per manufacturer recommendations, may have resulted in measurement error with the attachment not secured within the load cell and the participants reported difficulties in generating force when using the ankle attachment. Previous research has commented on the difficulties associated with the ankle attachments on the KinCom dynamometer (Kaminski et al., 1995). The SEM and MDC were also much higher for the KinCom for assessment of ankle strength and RFD compared with the HHDs. It may be useful for future research to validate HHD measures of ankle strength and RFD against other devices such as laboratory-based dynamometers from different manufacturers or custom-built load cells. It should also be noted that the KinCom was not used for four participants whilst the mechanism that moved the KinCom was being repaired, which should not have affected any of the data, resulting in a lower sample size for the validity analyses (further details in Appendix B).

4.6 Conclusion

For the majority of variables assessed in the current study, the HHDs were a reliable and valid tool when assessing isometric lower limb strength and RFD. However, the psychometric properties of HHDs shown in the current study do not necessarily translate to acceptable reliability and validity in clinical populations. Further research is required to examine the psychometric properties of HHD when measuring isometric strength and RFD in clinical populations.

Given the issues identified with the KinCom for assessment of ankle strength and RFD, the fixed dynamometer may not have been the most appropriate criterion reference to use,

although it is commonly stated as the 'gold standard' of muscle strength assessment for the ankle. Despite the less than favourable validity results of ankle strength and RFD and because of the previously published strong associations between HHD measures of ankle strength and gait velocity shown in Study Two (Mentiplay et al., 2015a), it was decided to continue using the HHDs in the subsequent studies as they currently provide the most clinically feasible measure of strength and RFD.

Hand-held dynamometers may be able to provide additional, valuable information for clinicians, especially in clinical populations with functional impairments. Assessment of isometric power in clinical populations using HHDs is warranted to determine the relationship between this measure and physical function. Study Two has informed the design of the subsequent studies of this thesis to use HHDs to examine how isometric strength and RFD relate to gait following stroke.

CHAPTER FIVE: ASSOCIATIONS OF GAIT VELOCITY WITH ISOMETRIC STRENGTH AND POWER FOLLOWING STROKE (STUDY THREE)

5.1 Preamble

Study One identified a lack of high quality research that has examined the associations between isometric muscle strength and gait velocity following stroke, which has led to equivocal correlation values being reported across the majority of lower limb muscle groups. One of the primary aims of the current study (Study Three) will be to contribute high quality research to investigate the strength of which lower limb muscle group has the strongest association with gait velocity.

Isometric muscle power has previously shown a stronger association, over isometric strength, with physical function in a variety of clinical populations (Maffiuletti et al., 2010; Moreau et al., 2012; Winters et al., 2014). A previous study in the stroke population also showed encouraging results for the measurement of isometric knee extensor muscle power to explain more of the variance in gait velocity over knee extensor strength (Pohl et al., 2002). Despite these findings, the previous studies assessing RFD (Maffiuletti et al., 2010; Moreau et al., 2012; Pohl et al., 2002) have used expensive and cumbersome equipment which limits their clinical feasibility and have typically only measured one lower limb muscle group (primarily the knee extensors). Therefore, a further aim of the current study was to examine whether isometric muscle power had stronger associations with gait velocity following stroke across multiple lower limb muscle groups, when compared with isometric muscle strength, as measured using HHD.

Study Two demonstrated the potential for isometric muscle power to be reliably measured using HHDs in a healthy and unimpaired cohort. The psychometric properties of HHDs for isometric power assessment are currently unknown in the stroke population and therefore, the current study (Study Three) will assess the test-retest reliability of HHD to measure isometric muscle strength and power in the stroke population.

It should be noted that torque (instead of force) will be used in Studies Three and Four. All reliability and validity analyses in Study Two were conducted using a within participant design and, hence, would not have been influenced by the length of the lever arm, which is used to calculate torque. However, as Studies Three and Four involve analyses that are conducted across participants, the force data will be normalised and presented as torque to account for any differences in lever arm length between the participants.

5.2 Introduction

Stroke is associated with a number of acute and long-term impairments, such as decreased muscle strength and reduced balance ability (Dorsch, Ada, & Canning, 2016; Geurts et al., 2005), which can substantially impact on the performance of daily activities. A key goal of rehabilitation following stroke is often the restoration of walking at a speed that allows for community reintegration (e.g. adequate gait velocity for crossing safely at busy pedestrian crossings). This goal is reflected by the relatively large amount of time spent by physiotherapists on gait retraining during rehabilitation sessions (Latham et al., 2005; Tole et al., 2014). Previous research has demonstrated strong associations between gait velocity and physical activity levels (Mudge & Stott, 2009; Zalewski & Dvorak, 2011), further highlighting the importance of gait velocity measurements after stroke. In order to effectively improve gait velocity, it may be pertinent to understand the impairments that contribute to reduced walking speed following stroke.

Examining how reduced muscle strength correlates with activities of daily living and physical function following stroke has been the focus of much research in the past 30 years. Decreased muscle strength has been shown to be associated with difficulty performing functional tasks such as stair climbing, sitting-to-standing and the Timed Up and Go (Bonnyaud et al., 2013; Lomaglio & Eng, 2005; Ng & Hui-Chan, 2013). A recent systematic review (Study One) examined how isometric lower limb strength correlated with gait velocity following stroke (Mentiplay et al., 2015a). The systematic review found 21 articles that examined a variety of lower limb muscle groups (Mentiplay et al., 2015a). Across the included studies there was large variation in the bivariate correlations between lower limb muscle strength and gait velocity, with differences between the studies in the sample size utilised, the muscle groups assessed and the protocols for strength testing (Bohannon, 1989b; Dorsch et al., 2012; Kim & Eng, 2003a; Patterson et al., 2007; Svantesson, Osterberg, Grimby, & Sunnerhagen, 1998). Despite the systematic review suggesting the strength of the ankle dorsiflexors of the paretic side to have the largest bivariate association with gait velocity following stroke, many of the included studies measured only one lower limb muscle group (primarily the knee extensors), included small sample sizes and had low methodological quality. This highlights the need for further research to determine how isometric strength relates to gait velocity after stroke and which specific muscle groups explain the most variance in gait velocity.

Another measure that can be quantified from isometric testing is the RFD, which can give an indication of explosive muscle strength (Aagaard et al., 2002). The RFD is commonly normalised to the lever arm of the segment being assessed, which converts the force recorded into torque and subsequently RTD is often used. The RTD, instead of RFD, will be used in this study. The time taken to reach maximal strength during an isometric contraction can take 300 milliseconds or longer (Aagaard et al., 2002). Additionally, only sub-maximal

muscle contractions are required during gait (Ericson, Nisell, & Ekholm, 1986) and therefore, RTD could potentially provide a stronger association with gait velocity compared with muscle strength. The measure of RTD has been shown to provide a stronger link, compared to muscle strength, with a range of measures of physical function in different clinical populations, such as cerebral palsy and those with knee osteoarthritis (Hsieh et al., 2015; Moreau et al., 2012; Winters et al., 2014; Winters & Rudolph, 2014). Only one previous study in the stroke population examined whether isometric muscle strength or RTD (of the knee extensors) contributed more to the variance in gait velocity (Pohl et al., 2002). Despite RTD explaining more of the variance in gait velocity compared with strength, the regression model explained only 12% of the variance (Pohl et al., 2002). The poor relationship with gait velocity may be explained by the previous study measuring the strength and RTD of the knee extensors only, which are not a primary muscle group for forward propulsion during gait (Liu et al., 2006; Olney et al., 1991) and have only a modest association with gait velocity following stroke (Mentiplay et al., 2015a). Despite the promising results for RTD, further examination of the contribution of RTD to gait velocity above and beyond maximal strength of other lower limb muscle groups may be necessary.

Current methods to assess RTD require expensive and burdensome equipment, generally precluding their use in clinical settings. Study Two in this thesis demonstrated the ability of HHDs to reliably assess RTD in an unimpaired cohort (Mentiplay et al., 2015b). Only a small number of studies have examined the test-retest reliability of HHD for measurement of isometric strength in neurological populations, with equivocal findings in mixed cohorts including stroke, traumatic brain injury and spinal cord injury (correlations = 0.09 to 0.99) (Bohannon, 1986b; Morris, Dodd, & Morris, 2008; Riddle, Finucane, Rothstein, & Walker, 1989) and no study has examined the ability of HHD to reliably assess RTD in a stroke population.

The primary aims of the current study were to: 1) comprehensively assess the relationship of isometric lower limb strength and RTD with gait velocity after stroke; 2) examine which measure (isometric strength or RTD) explains more of the variance in gait velocity following stroke; and 3) investigate which lower limb muscle group has the strongest relationship with gait velocity after stroke. A secondary aim was to assess the test-retest reliability of HHD for assessment of isometric strength and RTD in a stroke cohort.

5.3 Methods

5.3.1 Participants

A convenience sample of adults 21 years or older was recruited from outpatient physiotherapy and rehabilitation clinics at two major hospitals in Australia and Singapore. The legal age for consent in research studies in Singapore is 21 years and consequently only participants above this age were recruited. Participants in Australia were recruited in Melbourne at the Epworth Hospital (largest private health care group in Victoria, Australia), at two campuses in Richmond and Camberwell. Recruitment in Singapore was through the Singapore General Hospital (largest public hospital in Singapore).

Included participants were at least three months following stroke to reduce the likelihood of change between assessments for reliability analyses, with previous research suggesting that the majority of recovery occurs within the first three months after stroke (Skilbeck, Wade, Hewer, & Wood, 1983; Wade, Wood, & Hewer, 1985). Participants were required to have the ability to walk at least 10 metres independently, with close supervision if required (no contact assistance), to be able to perform the assessment of gait velocity. Participants were required to perform the gait assessment without any assistive devices (e.g. canes or ankle foot orthoses), even if it was usual for them to use aids for longer distances. Although some

people required assistive devices to walk, such devices may alter the spatiotemporal and kinematic variables as well as the muscle contributions during gait and thus could affect the correlation between gait and measures of muscle function (Dorsch et al., 2012; Kuan et al., 1999). These inclusion criteria may have resulted in participants who had a higher level of ability post stroke, although these were crucial to ensure the associations revealed the true impact of strength on gait velocity.

Exclusion criteria were cerebellar stroke, due to the different clinical presentation and gait patterns (e.g. ataxia) of such strokes (Edlow et al., 2008; Kase et al., 1993; Tohgi et al., 1993). Participants were also excluded if they had any cognitive issues where they were unable to follow instruction, as indicated by a score below seven on the Abbreviated Mental Test Score (Hodkinson, 1972). The threshold score of seven has been commonly used previously to determine cognitive impairment and has shown strong sensitivity and specificity (Jackson, Naqvi, & Sheehan, 2013). This cognitive assessment has also previously been used in the stroke population to determine if cognitive impairment is present (Douiri, Rudd, & Wolfe, 2013) and was used in this study to ensure participants understood the requirements of participation and could provide their own informed consent. Participants were excluded if they had any other diagnosed medical comorbidities that would preclude or alter participation in tests of muscle function and gait such as severe arthritis or cardiorespiratory conditions. As the population of interest was mainly an elderly population, some included participants did have mild arthritis or cardiac issues. These comorbidities were discussed on an individual basis with the participant and clinician, if needed, to determine whether such health concerns would affect their gait pattern or muscle function.

Data collection for Study Three had ethical approval from the relevant ethics committees at each hospital in Australia and Singapore as well as registration through the Australian

Catholic University (see Appendix H). All participants provided written informed consent prior to study enrolment. Based on a power calculation for a correlation study with 90% power, a two-tailed significance level set at 0.05 and an expected average bivariate relationship of 0.40 determined from a similar previous study (Dorsch et al., 2012), a sample size of 62 participants was required for this study (Portney & Watkins, 2009).

5.3.2 Procedure

A cross-sectional, observational design with a test-retest reliability component was utilised. Gait velocity and measures of isometric strength and power were assessed once at the hospital from which participants were recruited. A subset of participants who were willing and able to repeat the assessment of isometric muscle strength and power returned for a second session on a separate day (ideally 7 to 14 days later). All procedures were kept consistent across sites and the same assessor (thesis author BFM) performed all tests of gait velocity and isometric muscle function in Australia and Singapore. Characteristics collected from participants included age, gender, race, height and weight. Pertinent stroke details were also collected including time since stroke, paretic side (left or right), type of stroke (ischaemic or haemorrhage) and assistive devices normally used when ambulating outdoors.

Measurement of gait velocity was assessed first and consisted of performing four trials of the 10 Metre Walk Test (Collen et al., 1990); two at a comfortable pace and two at a fast pace. The 10 Metre Walk Test is frequently used in the clinical setting, as well as for research purposes, and has shown excellent test-retest reliability in the stroke population with ICC values above 0.94 (Flansbjer et al., 2005; Van Bloemendaal, Van De Water, & Van De Port, 2012). Participants walked barefoot and without assistive devices over a 14m walkway, with the central 10 metres timed using a stopwatch to calculate gait velocity (in m/s). The stopwatch started when the participants' leading foot crossed the 2m line and ended when

the leading foot crossed the 12m line. The 2m buffer at each end removes any influence of acceleration or deceleration on the timed component of the walk. Instructions to the participants were to walk at a comfortable pace until the end of the walkway (for comfortable pace) and to walk as fast as safely possible until the end of the walkway (for fast pace). The fastest gait speed recorded (shortest time) was chosen for analysis for each pace. The thesis author (BFM) conducted all assessments of gait velocity.

Isometric muscle strength and power of the lower limb was measured using a HHD as described in detail in Study Two, Section 4.3 (Mentiplay et al., 2015b). The HHD used was the Lafayette Manual Muscle Testing System Model-01165 (Lafayette Instrument Company, Lafayette IN, USA). There were no apparent differences between the two HHDs assessed in Study Two, however the Lafayette device was chosen over the Hoggan micro*FET*2 due to the more straightforward data collection procedures that did not require a computer during testing. The software interface of the Lafayette HHD was also much easier to use compared with the Hoggan HHD, with the Hoggan software often losing recorded data during Study Two.

In our pilot testing of persons following stroke, the padding of the Lafayette HHD provided by the manufacturer was not deemed adequate for participant comfort, therefore additional foam padding (12mm thick EVA foam) was placed over the dynamometer pad to protect the participant from potential abrasions or pain (see Figure 5.1). Seven lower limb muscle groups were assessed in the following order: hip flexors, knee extensors and knee flexors (seated); ankle plantarflexors, ankle dorsiflexors and hip abductors (supine); and hip extensors (prone). The positions of assessment can be seen in Study Two (Figure 4.1 on page 94). Due to the lower strength levels of those following stroke (compared with the healthy cohort), the assessment of the ankle plantarflexors and knee extensors did not require

the plinth to be placed close to a wall as was done in Study Two. The muscle groups assessed were the seven main muscle groups identified in the systematic review of Study One and were assessed in Study Two. The hip adductors were not measured in the stroke cohort (although they were measured in Study Two) in an attempt to reduce the time and effort demands of assessment. The order of muscle groups was chosen to minimise the position changes required for the participants. Each contraction was an isometric MVC and participants were asked to push or pull as hard and as fast as they could against the HHD. This enabled the calculation of isometric strength and RTD from the same trial. The non-paretic limb was assessed first, with one, unrecorded practice trial followed by two recorded trials. The paretic limb of the same muscle group was then assessed with two recorded trials. Rest and water were provided to each participant throughout testing as required. The same assessor (thesis author BFM, male with two years of experience using HHD with healthy and neurological populations) performed all assessments. The assessor has demonstrated acceptable reliability in a healthy cohort for measures of lower limb isometric muscle strength and power (Assessor-A in Study Two) (Mentiplay et al., 2015b).

Figure 5.1. Lafayette device used for strength and power assessment with additional foam padding attached.

5.3.3 Data analysis

The data analysis for HHD assessment for this study was identical to Study Two. The time series of the raw force data was filtered using a zero-phase shift 10Hz lowpass 4th order Butterworth filter and then resampled to 1000Hz (the Lafayette device samples at 40Hz) using cubic spline interpolation. The HHD recorded force in kilograms and was then converted to Newtons. The force in Newtons was then converted to torque by multiplying by the lever arm (metres). The lever arm is the distance between the dynamometer pad and the joint centre being tested. A further step in analysis was to normalise the torque to body mass (kilograms) to control for participants with varying body mass levels.

Isometric strength (Nm/kg) was calculated as the highest reading across the two trials. Isometric muscle power was assessed using RTD. The method employed in this study for calculation of RTD was the method that had the strongest reliability, as described in Study Two, Section 4.3 (Mentiplay et al., 2015b). Briefly, successive time intervals of 200ms

across the raw force trace were scanned (e.g. sample 1 to 201, 2 to 202, 3 to 203) to determine the peak RTD (Nm/s/kg) across the trial. The highest peak RTD recorded across the two trials was used for analysis. If participants were unable to generate any force against the HHD, a score of zero was recorded for that muscle group for both strength and RTD.

5.3.4 Statistical analysis

Descriptive statistics (means with standard deviations and medians with interquartile ranges for continuous variables and frequencies with percentages for categorical variables) were used to describe participant characteristics and variables of gait velocity and muscle function. The assumption of normality for some participant characteristics and variables was not met and therefore, to provide a consistent analysis when examining differences between the Australian and Singaporean cohorts, Mann-Whitney U tests for continuous variables and Chi-Squared tests for categorical variables were performed. To test associations between variables it was decided to use Spearman correlations to provide a consistent analysis as Spearman correlations are robust to non-normally distributed data and commonly used as the nonparametric alternative of the correlation coefficient (Bishara & Hittner, 2012).

Test-retest reliability of the HHD measures of isometric strength and RTD was assessed in the same manner as Study Two using a two-way random effects model $ICC_{(2,k)}$ with 95% confidence intervals, which includes systematic error and k represents the average of k scores from each participant. The SEM and MDC were also calculated. The SEM and MDC were calculated based on the formulas provided by Portney and Watkins (2009) and expressed as percentages of the mean (as described in Study Two). The SEM provides an indication as to what can be considered measurement error whilst the MDC reflects the amount of change required to indicate that the change is not a result of the measurement error.

To examine the first aim of the current study, to provide a comprehensive analysis of the relationship between strength/RTD and gait velocity, correlations were performed with and without adjustment for confounders. Unadjusted associations were determined using Spearman correlations to assess bivariate correlations between each muscle group and gait velocity.

Although not direct aims of the current study, this study included some secondary analyses of the data. Secondary analyses included importing the bivariate correlations from the current study into Figure 3.2 from the systematic review in Study One to provide a visual comparison between the current study and previous literature. Due to the international aspect of the current study, bivariate correlations were also examined for the association between gait velocity and strength/RTD measures for those recruited in Australia and Singapore separately. To examine any effects of the time since stroke on the association between strength/RTD and gait velocity, bivariate correlations were performed for those who were less than one year after stroke and those who were greater than one year after stroke. Lastly, bivariate correlations were also performed to examine the association between the two gait velocity tests as well as between strength and RTD of each muscle group. These correlations were performed to provide information on the redundancies of each test, with high correlation values indicating potential redundancy of measures.

Continuing the analysis for the first aim of the study, adjusted relationships were examined with multivariable linear regressions to analyse the relationship between each muscle group with gait velocity, adjusting for pertinent population confounders of age, gender, time since stroke and country of recruitment (with body mass and lever arm already adjusted for within the strength/RTD scores). The assumption of normality was not met for the covariate of time since stroke and therefore it was log transformed prior to all regression analyses. The

regression model, with gait velocity entered as the dependent variable, was first created with a base model of the covariates. One variable was then entered into the model (e.g. ankle dorsiflexor RTD) and this was repeated for each measure of muscle function. This was also repeated for both gait velocity measures (comfortable and fast paced gait velocity). The change statistics were then examined to determine the incremental value of each variable over the base model, with the change in R^2 (increment) and the *p*-value of the change reported. To provide an example: a base model R^2 of 0.125 (only covariates included) and a total combined R^2 (with ankle dorsiflexor RTD included) of 0.525 would result in an R^2 increment of ankle dorsiflexor RTD over the covariates of 0.400 and a significant *p*-value of 0.02 (arbitrary values used for the purposes of this example). This example would suggest that ankle dorsiflexor RTD provides significant incremental value for the relationship with gait velocity over and above the covariates.

To provide a clinical interpretation of these regression results and allow for comparisons of effect sizes for each model, mean differences for an interquartile increase of the strength/RTD scores were estimated. Mean differences (with 95% confidence intervals) were calculated from the unstandardised beta coefficients multiplied by the interquartile range for each measure of strength and RTD. This provides an indication of the difference in gait velocity for participants within our cohort with an interquartile increase in strength or RTD levels.

Whilst the first regression models can be used to compare strength and RTD by ranking the R^2 increment, a formal comparison was required to statistically determine which measure, strength or RTD, had the strongest relationship with gait velocity (second aim of the study). A partial F-test was used to determine which measure significantly contributed additional value to the model (Harrell Jr., 2015). This method was performed by creating a base model

with covariates of age, gender, time since stroke and country recruited, with gait velocity as the dependent variable. A total model for each muscle group was then created with the base model included with both measures of strength and RTD for a particular muscle group (e.g. adding both ankle dorsiflexor strength and RTD to the base model). Then strength was removed from the model to determine the individual effect of strength on the total model. This was then repeated by leaving strength in the model, but removing RTD to determine the individual effect of RTD on the total model. Reported in the results are the total model R^2 (model includes the covariates and both strength and RTD), the reduction in R^2 for removal of each measure of strength and RTD from the model and the *p*-value when each measure is removed (termed the *p*-value decrement). For example: a total model R^2 of 0.600 that contains the covariates plus ankle dorsiflexor strength and RTD, removing dorsiflexor RTD from the total model results in the model R^2 dropping to 0.400 (reduction in R^2 of 0.200 and *p*-value decrement of 0.02) and removing dorsiflexor strength from the total model results in the model R^2 dropping to 0.590 (reduction in R^2 of 0.010 and *p*-value decrement of 0.85). These changes would indicate that RTD provides additional value in the relationship with gait velocity over strength for the ankle dorsiflexors (arbitrary values used for the example). If strength and RTD both return significant *p*-value decrements or both return non-significant *p*-value decrements, then no statistical difference exists between measures.

The last step in analysis involved comparing each muscle group to determine which muscle group had the strongest relationship with gait velocity (third aim of this study). The partial F-test was also used for this formal comparison. As previously, the first step was to create a base model with covariates entered and gait velocity as the dependent variable. The muscle groups that demonstrated the largest associations and relationships with gait velocity, as determined from the previous bivariate and multivariate analyses, were then compared on a

head-to-head basis. The variable (either strength or RTD) that provided additional value over the other was used for this step of analysis. A total model was created with the base model of covariates and two opposing muscle groups (e.g. ankle dorsiflexors and ankle plantarflexors). The *p*-value decrement was then examined as per the previous analyses to determine which muscle group provided additional value over the other one. If there were more than two muscle groups to compare, this step was repeated multiple times so that each muscle group was compared head-to-head against each other muscle group.

The regression residuals for all models were examined to determine if they adequately met the assumptions for least squares regressions. Significance was set at $p < 0.05$ for all analyses. For reliability analyses, the ICC values were interpreted based on suggestions by Portney and Watkins (2009), with values taken as excellent (≥ 0.90), good (0.75 to 0.89), moderate (0.50 to 0.74), or poor (< 0.50). For bivariate associations, Spearman values were interpreted based on the suggestions of Evans (1996), with values taken as very strong (≥ 0.80), strong (0.60 to 0.79), moderate (0.40 to 0.59), weak (0.20 to 0.39), or very weak (< 0.20). The differences in interpretations between reliability and correlations were used to ensure stricter thresholds for interpretation of the reliability analyses. All analyses were performed with the Statistical Package for Social Sciences version 23 (IBM Corp., Armonk, NY USA).

5.4 Results

5.4.1 Participant characteristics and outcome measures

In total, 63 participants were recruited (age: 60 ± 13 years; gender: 54% male; time since stroke: 39 ± 51 months), with 22 recruited from Australia and 41 from Singapore. The characteristics of the included participants are provided in Table 5.1. Participant

characteristics demonstrated significant differences between the Australian and Singaporean cohorts for race and type of stroke, with no significant difference for any other characteristic.

The variables of gait velocity as well as isometric strength and RTD are shown in Table 5.2. It should be noted that 13 participants were unable to lay prone due to discomfort or pain with positioning of the upper limb in prone. Consequently, the hip extensors were tested in only 50/63 participants. There were no significant differences between the cohorts in outcome measures for either gait velocity or paretic side muscle strength/RTD (Table 5.2). Differences between the Australian and Singaporean cohorts were observed in the non-paretic side for strength and RTD.

Table 5.1. Participant characteristics for Study Three

	Total (n = 63)	Australia (n = 22)	Singapore (n = 41)	Difference between groups
Gender, male *n* (%)	34 (54%)	10 (45%)	24 (59%)	$p = 0.32$
Age (years)	60 ± 13 (51/**59**/71)	60 ± 16 (49/**59**/74)	59 ± 11 (51/**59**/69)	$p = 0.68$
Height (cm)	164 ± 10 (158/**163**/171)	167 ± 9 (160/**165**/176)	162 ± 10 (154/**163**/170)	$p = 0.16$
Mass (kg)	67 ± 14 (58/**64**/75)	72 ± 18 (57/**71**/84)	64 ± 11 (58/**64**/69)	$p = 0.16$
Race				***p* < 0.01***
Caucasian, *n* (%)	20 (32%)	20 (91%)	0 (0%)	
Chinese, *n* (%)	36 (57%)	1 (4.5%)	35 (85%)	
Other, *n* (%)	7 (11%)	1 (4.5%)	6 (15%)	
Time since stroke (months)	39 ± 51 (4/**20**/60)	57 ± 69 (4/**23**/84)	30 ± 35 (4/**15**/46)	$p = 0.15$
Stroke paretic side, left *n* (%)	33 (52%)	11 (50%)	22 (54%)	$p = 0.78$
Type of stroke				***p* = 0.04***
Haemorrhage, *n* (%)	16 (25%)	9 (41%)	7 (17%)	
Infarct, *n* (%)	46 (73%)	12 (54.5%)	34 (83%)	
Both, *n* (%)	1 (2%)	1 (4.5%)	0 (0%)	
Assistive devices worn outdoors#				$p = 0.97$
None, *n*	37	13	24	
Ankle foot orthosis, *n*	7	7	0	
Single point stick, *n*	17	6	11	
Quad point stick, *n*	4	0	4	
Wheelchair, *n*	2	0	2	

Note: Continuous variables reported as mean ± standard deviation (25^{th}/**50^{th}**/75^{th} percentiles). The 'difference between groups' column reports statistical differences between the Australian and Singaporean cohorts using the Mann-Whitney U test for continuous variables and the Chi-Squared test for categorical variables. ***** = significant difference between Australian and Singaporean cohorts; # = assistive devices listed were not used during testing, these are the usual assistive devices participants used to ambulate outdoors (some participants used multiple assistive devices, therefore percentages are not provided). Chi-Squared for 'assistive devices worn outdoors' used dichotomised data for either yes or no.

Table 5.2. Gait and muscle function outcome measures

	Total (n = 63)	Australia (n = 22)	Singapore (n = 41)	Difference between groups
Gait velocity (m/s)				
Comfortable pace	0.85 ± 0.37 (0.50/**0.91**/1.13)	0.74 ± 0.31 (0.44/**0.78**/1.05)	0.91 ± 0.38 (0.61/**0.96**/1.18)	$p = 0.05$
Fast pace	1.07 ± 0.47 (0.59/**1.12**/1.42)	0.92 ± 0.42 (0.55/**0.94**/1.22)	1.15 ± 0.48 (0.84/**1.17**/1.57)	$p = 0.06$
Paretic strength (Nm/kg)				
Ankle dorsiflexors	0.13 ± 0.09 (0.05/**0.13**/0.19)	0.10 ± 0.09 (0.02/**0.10**/0.18)	0.15 ± 0.09 (0.08/**0.14**/0.24)	$p = 0.06$
Ankle plantarflexors	0.22 ± 0.12 (0.15/**0.22**/0.27)	0.18 ± 0.10 (0.07/**0.18**/0.26)	0.24 ± 0.13 (0.16/**0.22**/0.30)	$p = 0.12$
Hip abductors	0.75 ± 0.35 (0.48/**0.65**/1.01)	0.82 ± 0.37 (0.59/**0.82**/1.06)	0.71 ± 0.34 (0.48/**0.60**/0.94)	$p = 0.12$
Hip extensors#	0.83 ± 0.38 (0.52/**0.81**/1.01)	0.99 ± 0.45 (0.73/**0.87**/1.12)	0.75 ± 0.31 (0.44/**0.72**/0.96)	$p = 0.05$
Hip flexors	0.59 ± 0.24 (0.38/**0.60**/0.74)	0.63 ± 0.22 (0.44/**0.61**/0.75)	0.57 ± 0.25 (0.35/**0.50**/0.74)	$p = 0.33$
Knee extensors	1.00 ± 0.34 (0.76/**0.98**/1.22)	0.93 ± 0.35 (0.60/**0.95**/1.20)	1.04 ± 0.34 (0.79/**0.99**/1.22)	$p = 0.25$
Knee flexors	0.49 ± 0.28 (0.31/**0.45**/0.69)	0.44 ± 0.29 (0.18/**0.33**/0.71)	0.52 ± 0.27 (0.33/**0.49**/0.68)	$p = 0.23$
Paretic RTD (Nm/s/kg)				
Ankle dorsiflexors	0.17 ± 0.15 (0.05/**0.15**/0.26)	0.12 ± 0.11 (0.02/**0.09**/0.22)	0.20 ± 0.16 (0.07/**0.16**/0.27)	$p = 0.08$
Ankle plantarflexors	0.36 ± 0.24 (0.20/**0.32**/0.45)	0.29 ± 0.18 (0.13/**0.28**/0.42)	0.40 ± 0.26 (0.22/**0.33**/0.46)	$p = 0.18$
Hip abductors	1.12 ± 0.71 (0.65/**0.92**/1.45)	1.26 ± 0.85 (0.79/**1.10**/1.52)	1.05 ± 0.62 (0.62/**0.84**/1.34)	$p = 0.28$
Hip extensors#	1.33 ± 0.78 (0.74/**1.16**/1.82)	1.66 ± 0.99 (1.01/**1.36**/2.15)	1.16 ± 0.60 (0.68/**1.02**/1.45)	$p = 0.06$
Hip flexors	1.07 ± 0.58 (0.59/**1.00**/1.46)	1.19 ± 0.61 (0.74/**1.07**/1.60)	1.01 ± 0.56 (0.56/**0.96**/1.30)	$p = 0.19$
Knee extensors	1.57 ± 0.82 (0.97/**1.30**/1.95)	1.47 ± 0.67 (0.94/**1.59**/1.89)	1.62 ± 0.89 (0.96/**1.27**/2.05)	$p = 0.95$
Knee flexors	0.74 ± 0.55 (0.32/**0.64**/1.02)	0.71 ± 0.59 (0.25/**0.55**/1.11)	0.76 ± 0.53 (0.36/**0.64**/1.02)	$p = 0.49$
Non-paretic strength (Nm/kg)				
Ankle dorsiflexors	0.23 ± 0.07 (0.18/**0.22**/0.28)	0.25 ± 0.07 (0.20/**0.24**/0.29)	0.23 ± 0.08 (0.17/**0.22**/0.28)	$p = 0.26$
Ankle plantarflexors	0.36 ± 0.12 (0.27/**0.34**/0.40)	0.39 ± 0.13 (0.30/**0.36**/0.44)	0.34 ± 0.11 (0.26/**0.32**/0.38)	$p = 0.13$
Hip abductors	0.97 ± 0.33 (0.73/**0.92**/1.21)	1.21 ± 0.32 (1.07/**1.23**/1.34)	0.84 ± 0.26 (0.66/**0.81**/0.96)	***p* < 0.01***
Hip extensors#	1.09 ± 0.40 (0.85/**0.99**/1.29)	1.36 ± 0.44 (0.96/**1.33**/1.69)	0.96 ± 0.29 (0.78/**0.92**/1.08)	***p* < 0.01***
Hip flexors	0.75 ± 0.24 (0.58/**0.70**/0.91)	0.89 ± 0.24 (0.70/**0.83**/1.02)	0.68 ± 0.20 (0.53/**0.63**/0.80)	***p* < 0.01***
Knee extensors	1.22 ± 0.32 (1.01/**1.17**/1.41)	1.23 ± 0.34 (1.00/**1.16**/1.52)	1.22 ± 0.30 (1.02/**1.18**/1.41)	$p = 0.99$
Knee flexors	0.78 ± 0.24 (0.61/**0.78**/0.92)	0.85 ± 0.21 (0.69/**0.86**/1.01)	0.74 ± 0.24 (0.61/**0.72**/0.88)	***p* = 0.03***

Non-paretic RTD (Nm/s/kg)				
Ankle dorsiflexors	0.34 ± 0.16 (0.22/**0.31**/0.43)	0.34 ± 0.17 (0.22/**0.31**/0.43)	0.33 ± 0.16 (0.21/**0.31**/0.43)	p = 1.00
Ankle plantarflexors	0.57 ± 0.26 (0.39/**0.52**/0.68)	0.61 ± 0.27 (0.41/**0.57**/0.78)	0.55 ± 0.26 (0.36/**0.50**/0.65)	p = 0.34
Hip abductors	1.52 ± 0.83 (0.85/**1.30**/2.10)	2.05 ± 0.97 (1.29/**2.24**/2.69)	1.24 ± 0.59 (0.80/**1.14**/1.52)	***p* < 0.01***
Hip extensors#	1.92 ± 1.07 (1.21/**1.62**/2.55)	2.63 ± 1.33 (1.60/**2.55**/3.65)	1.55 ± 0.66 (1.15/**1.46**/1.84)	***p* < 0.01***
Hip flexors	1.36 ± 0.58 (0.95/**1.27**/1.62)	1.71 ± 0.63 (1.22/**1.62**/1.99)	1.17 ± 0.46 (0.81/**1.15**/1.39)	***p* < 0.01***
Knee extensors	1.88 ± 0.80 (1.29/**1.80**/2.44)	1.99 ± 0.85 (1.26/**1.97**/2.48)	1.83 ± 0.77 (1.28/**1.67**/2.30)	p = 0.40
Knee flexors	1.23 ± 0.58 (0.81/**1.13**/1.53)	1.45 ± 0.64 (0.95/**1.38**/1.78)	1.11 ± 0.52 (0.77/**1.07**/1.46)	p = 0.05

Note: Values reported are mean ± standard deviation (25^{th}/**50^{th}**/75^{th} percentiles). The 'difference between groups' column reports statistical differences between the Australian and Singaporean cohorts using the Mann-Whitney U test. ***** = significant difference between the Australian and Singaporean cohorts; # = hip extensors only measured in 50/63 participants (17/22 from Australia; 33/41 from Singapore); RTD = rate of torque development.

5.4.2 Test-retest reliability

The test-retest reliability for measurements of isometric strength and RTD of the paretic and non-paretic lower limb are provided in Table 5.3. There were 28 participants (14 from Australia and 14 from Singapore) who attended the second testing session. Participants returned for their second testing session on average 16 ± 16 days later (range of 2 to 69 days). The large range in time between sessions was due to the difficulties participants faced in attending the second session, with many participants providing consent for the second session only if they had other medical appointments on the same day. Despite the large variance in the time between sessions, the reliability results were similar between those who returned within 14 days and those who returned longer than 14 days later (see scatter plots in Appendix C for further information). Five participants were unable to lie prone for hip extension for both assessment sessions due to upper limb discomfort or pain and therefore only 23 participants were included in the test-retest reliability analysis for the hip extensors.

Results demonstrated excellent test-retest reliability (ICC ≥ 0.90) for both isometric muscle strength and RTD across all seven muscle groups of the paretic limb, with the exception of good test-retest reliability for hip abductor RTD (ICC = 0.89). Compared to the paretic limb, the non-paretic limb had slightly lower reliability results, although the majority of muscle groups for non-paretic strength and RTD still demonstrated excellent reliability (ICC ≥ 0.90), with the exception of good reliability for ankle dorsiflexor strength and RTD, hip abductor RTD and knee flexor RTD (ICC = 0.82 to 0.89).

The SEM and MDC showed large variation between muscle groups. The SEM ranged from 6 to 22% across the measures whilst the MDC had values from 18 to 60%. The SEM and MDC were higher for RTD compared with strength across all muscle groups.

Table 5.3. Test-retest reliability of hand-held dynamometry for the assessment of strength and rate of torque development following stroke

		Paretic side		Non-paretic side	
		Strength	**RTD**	**Strength**	**RTD**
Ankle dorsiflexors	ICC (95% CI)	0.95 (0.89 to 0.98)	0.92 (0.83 to 0.96)	0.82 (0.61 to 0.92)	0.89 (0.77 to 0.95)
	SEM (%)	13.31	21.70	12.34	14.98
	MDC (%)	36.90	60.16	34.20	41.54
Ankle plantarflexors	ICC (95% CI)	0.97 (0.93 to 0.99)	0.97 (0.94 to 0.99)	0.92 (0.82 to 0.96)	0.95 (0.88 to 0.98)
	SEM (%)	8.33	9.76	10.16	10.92
	MDC (%)	23.09	27.06	28.17	30.26
Hip abductors	ICC (95% CI)	0.95 (0.88 to 0.98)	0.89 (0.75 to 0.95)	0.91 (0.81 to 0.96)	0.88 (0.74 to 0.94)
	SEM (%)	8.90	17.25	9.89	16.95
	MDC (%)	24.67	47.82	27.43	46.99
Hip extensors#	ICC (95% CI)	0.94 (0.87 to 0.98)	0.93 (0.84 to 0.97)	0.93 (0.83 to 0.97)	0.94 (0.86 to 0.98)
	SEM (%)	11.54	16.49	9.40	12.57
	MDC (%)	31.98	45.71	26.06	34.83
Hip flexors	ICC (95% CI)	0.96 (0.91 to 0.98)	0.91 (0.81 to 0.96)	0.95 (0.89 to 0.98)	0.92 (0.82 to 0.96)
	SEM (%)	7.01	14.31	6.55	11.05
	MDC (%)	19.42	39.68	18.17	30.63
Knee extensors	ICC (95% CI)	0.93 (0.84 to 0.97)	0.94 (0.86 to 0.97)	0.94 (0.88 to 0.97)	0.90 (0.77 to 0.95)
	SEM (%)	7.88	12.36	6.49	13.25
	MDC (%)	21.83	34.25	18.00	36.72
Knee flexors	ICC (95% CI)	0.95 (0.90 to 0.98)	0.95 (0.88 to 0.98)	0.91 (0.80 to 0.96)	0.88 (0.74 to 0.94)
	SEM (%)	11.52	14.99	8.31	14.57
	MDC (%)	31.92	41.56	23.03	40.39

Note: RTD = rate of torque development; ICC (95% CI) = intraclass correlation coefficients with 95% confidence intervals; SEM (%) = standard error of measurement expressed as a percentage of the mean; MDC (%) = minimal detectable change expressed as a percentage of the mean; # = hip extensors measured in 23/28 participants (10/14 from Australia; 13/14 from Singapore).

5.4.3 Bivariate associations

Table 5.4 provides the Spearman correlations between gait velocity and isometric strength and RTD of the paretic side. All correlation values for the paretic side had significant weak to strong associations (rho = 0.35 to 0.72, $p < 0.05$). Three muscle groups (ankle dorsiflexors, ankle plantarflexors and knee flexors) showed consistent strong associations (rho = 0.62 to 0.72), while three other muscle groups (hip abductors, hip flexors and knee extensors) showed consistent moderate associations (rho = 0.44 to 0.56). The hip extensors showed weak to moderate associations (rho = 0.35 to 0.43).

Table 5.4. Bivariate correlations between strength and rate of torque development of the paretic side with gait velocity

	Comfortable Gait Velocity		Fast Gait Velocity	
	Strength	**RTD**	**Strength**	**RTD**
Ankle dorsiflexors	**0.62^**	**0.62^**	**0.64^**	**0.63^**
Ankle plantarflexors	**0.63^**	**0.63^**	**0.67^**	**0.64^**
Hip abductors	0.49	0.47	0.52	0.48
Hip extensors#	0.40	0.35	0.43	0.39
Hip flexors	0.53	0.51	0.56	0.54
Knee extensors	0.51	0.44	0.54	0.44
Knee flexors	**0.68^**	**0.62^**	**0.72^**	**0.65^**

Note: all Spearman correlations returned significant associations ($p < 0.05$). # = assessment of hip extensors only included 50/63 participants; ^ = strong correlation according to the thresholds of Evans (1996); RTD = rate of torque development.

The correlations between gait velocity and the non-paretic side strength and RTD are shown in Table 5.5. All associations were non-significant, with correlations ranging from very weak to weak (rho = 0.03 to 0.24, $p > 0.05$).

Table 5.5. Bivariate correlations between strength and rate of torque development of the non-paretic side with gait velocity

	Comfortable Gait Velocity		Fast Gait Velocity	
	Strength	**RTD**	**Strength**	**RTD**
Ankle dorsiflexors	0.17	0.22	0.15	0.21
Ankle plantarflexors	0.24	0.19	0.24	0.18
Hip abductors	0.05	0.11	0.06	0.13
Hip extensors#	0.10	0.03	0.11	0.10
Hip flexors	0.16	0.14	0.16	0.15
Knee extensors	0.10	0.11	0.13	0.11
Knee flexors	0.07	0.11	0.07	0.11

Note: all Spearman correlations revealed non-significant, very weak to weak associations between the non-paretic side strength and RTD and gait velocity following stroke ($p > 0.05$). # = assessment of hip extensors only included 50/63 participants; RTD = rate of torque development.

5.4.4 Secondary analyses

Figure 5.2, which was adapted from Figure 3.2 in Study One, displays the results from the current study in context to prior research. To maintain consistency with the rules of the figure from Study One, the correlations identified in the current study were from the fast gait velocity analysis and only included isometric strength of the paretic side. The current study showed a trend towards stronger bivariate correlations across all muscle groups compared to those previous studies identified in Study One with a relatively large sample size.

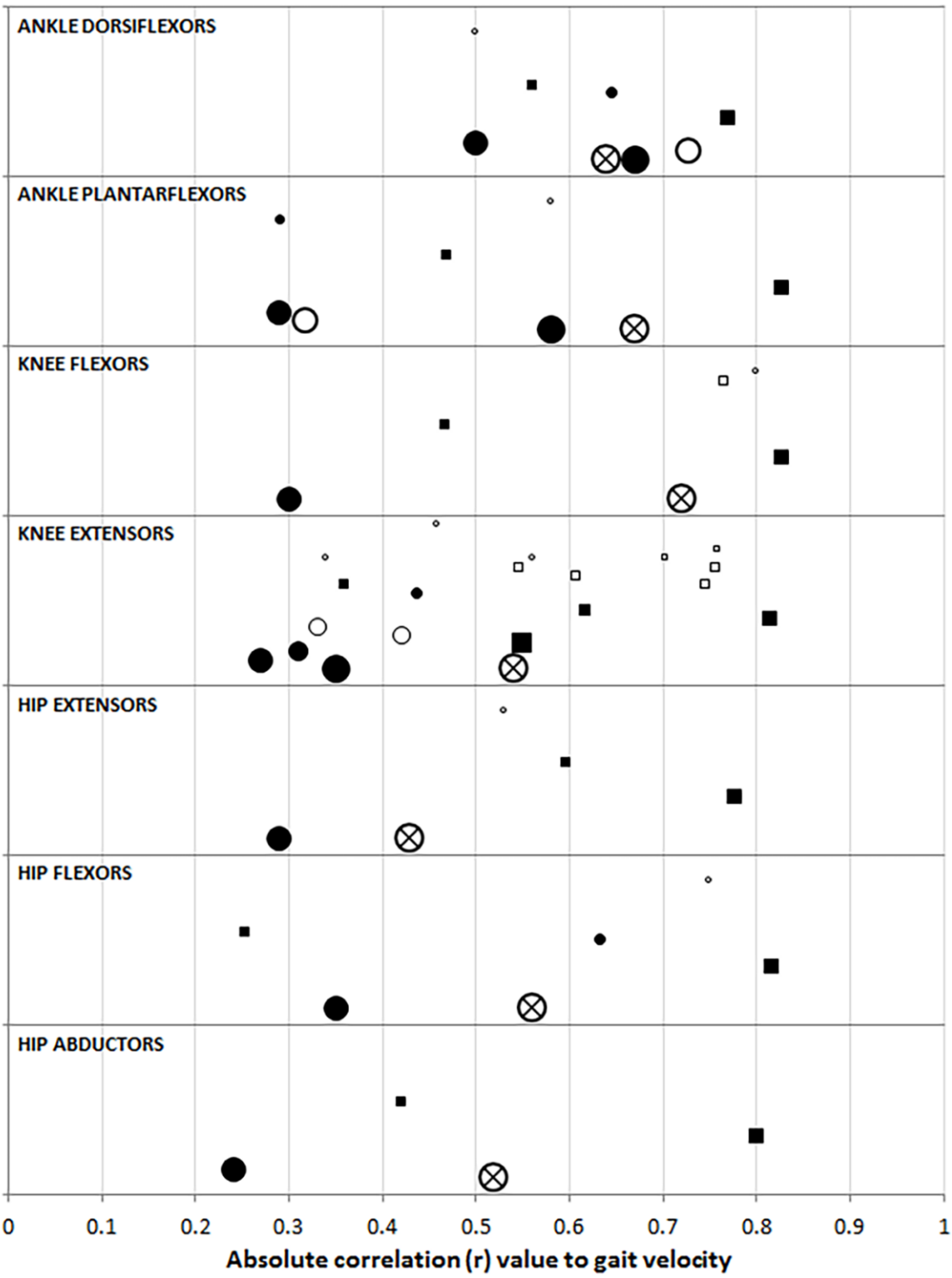

Figure 5.2. Associations between isometric lower limb strength and gait velocity. Points with a cross through them are from the current study. All formatting is kept consistent with Figure 3.2 (see Figure 3.2 on page 72 for more detail). Figure adapted with permission from (Mentiplay et al., 2015a).

As this study included participants from two different countries, the bivariate correlations between gait velocity and strength/RTD of the paretic side were examined for Australian participants (n = 22) and Singaporean (n = 41) participants separately (shown in Table 5.6). The results for the Singaporean cohort resemble the trend seen in the entire group for the associations between muscles strength/RTD and gait velocity following stroke, most likely due to two thirds of the entire group being from Singapore. Interestingly, the Australian cohort shows larger correlation values across all muscle groups. Most notably, hip abductor strength showed a strong correlation with gait velocity in the Australian cohort (rho = 0.73 and 0.74 for comfortable and fast gait velocity respectively) but only demonstrated moderate correlations for the entire group (rho = 0.49 and 0.52 respectively). A full comparison between the Australian sample and the entire group is problematic, primarily because the Australian cohort is contained within the entire cohort and the Australian cohort was relatively small (n = 22). As there were differences between the Australian and Singaporean cohorts in relation to the associations between gait velocity and strength/RTD, further multivariate analyses included country of recruitment as a covariate.

Table 5.6. Bivariate correlations between strength and rate of torque development of the paretic side with gait velocity comparing the Australian and Singaporean cohorts

	Comfortable Gait Velocity		Fast Gait Velocity	
	Strength	**RTD**	**Strength**	**RTD**
Australia (n = 22)				
Ankle dorsiflexors	**0.60**^	**0.65**^	**0.62**^	**0.65**^
Ankle plantarflexors	0.58	**0.60**^	**0.60**^	**0.61**^
Hip abductors	**0.73**^	0.45	**0.74**^	0.41 ns
Hip extensors#	0.58	0.36 ns	0.59	0.35 ns
Hip flexors	**0.75**^	0.58	**0.78**^	0.59
Knee extensors	0.57	0.50	0.56	0.48
Knee flexors	**0.71**^	**0.69**^	**0.76**^	**0.72**^
Singapore (n = 41)				
Ankle dorsiflexors	**0.66**^	**0.62**^	**0.68**^	**0.64**^
Ankle plantarflexors	**0.68**^	**0.64**^	**0.73**^	**0.67**^
Hip abductors	0.58	0.58	**0.61**^	0.59
Hip extensors#	0.56	0.55	0.58	**0.60**^
Hip flexors	0.54	**0.60**^	0.56	**0.62**^
Knee extensors	0.53	0.41	0.56	0.43
Knee flexors	**0.69**^	**0.63**^	**0.71**^	**0.63**^

Note: all Spearman correlations returned significant associations ($p < 0.05$), except those marked with 'ns'. # = assessment of the hip extensors only included in 17/22 Australian participants and 33/41 Singaporean participants; ^ = strong correlation according to the thresholds of Evans (1996); RTD = rate of torque development.

This study also included a large range in the time since stroke across the included participants (range from 93 days to 21 years), which may have affected the results. A comparison between those in our study who were less than one year after stroke (n = 27) and those who were greater than one year after stroke (n = 36) is provided in Table 5.7 for the paretic side. The group who were greater than one year following stroke seemed to show similar patterns to the results for the entire group, with the ankle dorsiflexors, ankle plantarflexors and knee flexors showing the largest associations with gait velocity (this may be due in part to the cohort greater than one year including more than half of the entire cohort). The group who were less than one year after stroke showed smaller association values across most muscle groups compared with those greater than one year after stroke

indicating that the association between isometric muscle strength and gait velocity may be reduced in those earlier in the recovery phase after stroke. Despite the reduced associations in those less than one year after stroke, the strength of the ankle plantarflexors still demonstrated the strongest association with gait velocity. As there were observable differences between the two cohorts, all multivariate analyses included time since stroke as a covariate.

Table 5.7. Bivariate correlations between strength and rate of torque development of the paretic side with gait velocity comparing those less than one year after stroke and those greater than one year after stroke

	Comfortable Gait Velocity		Fast Gait Velocity	
	Strength	**RTD**	**Strength**	**RTD**
< one year (n = 27)				
Ankle dorsiflexors	0.40	0.46	0.47	0.50
Ankle plantarflexors	0.51	0.45	**0.63^**	0.50
Hip abductors	0.47	0.55	0.49	0.51
Hip extensors#	0.38 ns	0.42 ns	0.43	0.47
Hip flexors	0.40	0.37 ns	0.43	0.39
Knee extensors	0.44	0.44	0.42	0.42
Knee flexors	0.48	0.34 ns	0.58	0.39
> one year (n = 36)				
Ankle dorsiflexors	**0.64^**	**0.63^**	**0.66^**	**0.66^**
Ankle plantarflexors	**0.60^**	**0.69^**	**0.61^**	**0.70^**
Hip abductors	0.53	0.51	0.54	0.50
Hip extensors#	0.37 ns	0.24 ns	0.38	0.27 ns
Hip flexors	0.53	**0.60^**	0.57	**0.63^**
Knee extensors	0.55	0.41	0.59	0.43
Knee flexors	**0.78^**	**0.75^**	**0.80^**	**0.74^**

Note: all Spearman correlations returned significant associations ($p < 0.05$), except those marked with 'ns'. Participants less than one year were 8/22 Australians and 19/41 Singaporeans, participants greater than one year were 14/22 Australians and 22/41 Singaporeans. # = assessment of the hip extensors only included in 22/27 participants less than one year and 28/36 participants greater than one year. ^ = strong correlation according to the thresholds of Evans (1996); RTD = rate of torque development.

The last step in the secondary analyses was to examine the correlations between variables of strength and RTD measures of the paretic side. Isometric strength and RTD of the paretic side showed a strong correlation between each muscle group (e.g. ankle dorsiflexor strength and ankle dorsiflexor RTD), indicating potential redundancy between measures (rho = 0.80 to 0.94). A full correlation matrix between strength and RTD of the paretic side is provided in Table 5.8. For gait velocity, there was a very strong correlation between the comfortable and fast paced gait velocity speeds (rho = 0.96), also indicating potential redundancy between measures.

Table 5.8. Correlation matrix between measures of isometric strength and rate of torque development for the paretic side

	ADF S	ADF RTD	APF S	APF RTD	HAB S	HAB RTD	HE S	HE RTD	HF S	HF RTD	KE S	KE RTD	KF S	KF RTD
ADF S	1.00													
ADF RTD	0.94	1.00												
APF S	0.84	0.82	1.00											
APF RTD	0.79	0.86	0.87	1.00										
HAB S	0.52	0.54	0.60	0.60	1.00									
HAB RTD	0.37	0.47	0.50	0.59	0.82	1.00								
HE S	0.43	0.46	0.51	0.53	0.77	0.63	1.00							
HE RTD	0.30	0.44	0.45	0.50	0.67	0.66	0.89	1.00						
HF S	0.65	0.64	0.69	0.66	0.78	0.58	0.71	0.56	1.00					
HF RTD	0.56	0.61	0.62	0.67	0.80	0.73	0.70	0.62	0.88	1.00				
KE S	0.50	0.54	0.62	0.66	0.77	0.69	0.65	0.60	0.74	0.72	1.00			
KE RTD	0.40	0.50	0.52	0.66	0.71	0.75	0.58	0.59	0.62	0.72	0.80	1.00		
KF S	0.82	0.83	0.78	0.79	0.68	0.58	0.60	0.48	0.80	0.73	0.65	0.54	1.00	
KF RTD	0.74	0.81	0.74	0.83	0.67	0.66	0.63	0.56	0.73	0.75	0.62	0.65	0.92	1.00

Note: all Spearman correlations returned significant associations ($p < 0.05$). S = strength; RTD = rate of torque development; ADF = ankle dorsiflexors; APF = ankle plantarflexors; HAB = hip abductors; HE = hip extensors; HF = hip flexors; KE = knee extensors; KF = knee flexors.

5.4.5 Multivariate linear regression models

Multivariate regression models examined the relationship between gait velocity and strength/RTD of the paretic side after adjusting for pertinent covariates. All of the regression models presented from here onwards adequately met the assumptions for least squares regressions. Table 5.9 provides the results of the multivariate linear regression. These results are reported with the base model R^2, the incremental value of each outcome measure over the base model (R^2 increment and *p*-value of the increment) and the total model R^2. The base model (containing age, gender, time since stroke and country recruited) showed an R^2 of 0.201 and 0.157 with comfortable and fast gait velocity as dependent variables, respectively. As the hip extensor muscle group contained only 50 participants, the base model was different with an R^2 of 0.281 and 0.211.

Examination of the *p*-value change statistics revealed that all measures of strength and RTD provided significant incremental value over a base model for the relationship with comfortable and fast gait velocity. The strength and RTD of the hip flexors, ankle plantarflexors, knee flexors and ankle dorsiflexors demonstrated the largest R^2 increment over a base model (in this order). This was evident for both comfortable (hip flexors R^2 increment = 0.299 and 0.268 for strength and RTD respectively; ankle plantarflexors R^2 increment = 0.291 and 0.253; knee flexors R^2 increment = 0.274 and 0.228; ankle dorsiflexors R^2 increment = 0.252 and 0.215) and fast gait velocity (hip flexors R^2 increment = 0.342 and 0.293 for strength and RTD respectively; ankle plantarflexors R^2 increment = 0.346 and 0.283; knee flexors R^2 increment = 0.337 and 0.271; ankle dorsiflexors R^2 increment = 0.299 and 0.252). Further analysis was needed to determine which measure (strength or RTD) and which muscle groups statistically had the strongest relationship with gait velocity.

Table 5.9. Regression results for the relationship between strength and rate of torque development with comfortable and fast gait velocity

	Comfortable Gait Velocity				Fast Gait Velocity			
	Base model R^2	**R^2 increment**	***p*-value of increment**	**Total R^2**	**Base model R^2**	**R^2 increment**	***p*-value of increment**	**Total R^2**
Strength (Nm/kg)								
Ankle dorsiflexors	0.201	0.252	**< 0.01***	0.453	0.157	0.299	**< 0.01***	0.457
Ankle plantarflexors	0.201	0.291	**< 0.01***	0.491	0.157	0.346	**< 0.01***	0.503
Hip abductors	0.201	0.211	**< 0.01***	0.412	0.157	0.263	**< 0.01***	0.420
Hip extensors#	0.281	0.133	**< 0.01***	0.414	0.211	0.146	**< 0.01***	0.357
Hip flexors	0.201	0.299	**< 0.01***	0.500	0.157	0.342	**< 0.01***	0.499
Knee extensors	0.201	0.138	**< 0.01***	0.339	0.157	0.173	**< 0.01***	0.330
Knee flexors	0.201	0.274	**< 0.01***	0.475	0.157	0.337	**< 0.01***	0.494
RTD (Nm/s/kg)								
Ankle dorsiflexors	0.201	0.215	**< 0.01***	0.416	0.157	0.252	**< 0.01***	0.409
Ankle plantarflexors	0.201	0.253	**< 0.01***	0.454	0.157	0.283	**< 0.01***	0.440
Hip abductors	0.201	0.199	**< 0.01***	0.400	0.157	0.215	**< 0.01***	0.373
Hip extensors#	0.281	0.075	**0.03***	0.356	0.211	0.087	**0.02***	0.298
Hip flexors	0.201	0.268	**< 0.01***	0.468	0.157	0.293	**< 0.01***	0.450
Knee extensors	0.201	0.131	**< 0.01***	0.331	0.157	0.158	**< 0.01***	0.315
Knee flexors	0.201	0.228	**< 0.01***	0.429	0.157	0.271	**< 0.01***	0.429

Note: results from linear regression models, with analyses adjusted for age, gender, time since stroke and country recruited (body mass and lever arm adjusted for within strength/RTD scores). R^2 increment is the change in R^2 of each variable over a base model (age, gender, time since stroke and country recruited). The *p*-value of increment is the significance level of the R^2 increment. Total R^2 is the total combined model with covariates (Base model R^2) and the independent variable (R^2 increment). All R^2 increment values returned a significant *p*-value change as indicated by bold text and * symbol. # = hip extensor models only include data from 50/63 participants; RTD = rate of torque development.

Table 5.10 provides a clinical interpretation of the previous regression results, which highlights the difference in gait velocity within our group of participants for an interquartile difference in strength or RTD. An example of this interpretation is provided in the footnote of the table. The values reported in Table 5.10 may be affected by the stability of the measures and due to the large SEM values between the muscle groups and outcome measures identified in Table 5.3, caution is needed when comparing the muscle groups in the results of Table 5.10.

Table 5.10. Interpretation of regression results

	Percentile		Comfortable Gait Velocity	Fast Gait Velocity
	25th	75th	Difference (95% CI)	Difference (95% CI)
Strength (Nm/kg)				
Ankle dorsiflexors	0.05	0.19	0.35 (0.22 to 0.49)	0.50 (0.32 to 0.68)
Ankle plantarflexors	0.15	0.27	0.23 (0.15 to 0.32)	0.33 (0.23 to 0.43)
Hip abductors	0.48	1.01	0.29 (0.16 to 0.43)	0.42 (0.26 to 0.59)
Hip extensors	0.52	1.01	0.18 (0.07 to 0.30)	0.25 (0.09 to 0.41)
Hip flexors	0.38	0.74	0.35 (0.23 to 0.47)	0.48 (0.33 to 0.63)
Knee extensors	0.76	1.22	0.22 (0.09 to 0.35)	0.32 (0.15 to 0.48)
Knee flexors	0.31	0.69	0.29 (0.18 to 0.39)	0.41 (0.28 to 0.55)
RTD (Nm/s/kg)				
Ankle dorsiflexors	0.05	0.26	0.29 (0.16 to 0.42)	0.40 (0.24 to 0.57)
Ankle plantarflexors	0.20	0.45	0.22 (0.13 to 0.30)	0.30 (0.19 to 0.41)
Hip abductors	0.65	1.45	0.21 (0.11 to 0.30)	0.28 (0.15 to 0.41)
Hip extensors	0.74	1.82	0.15 (0.02 to 0.29)	0.21 (0.03 to 0.40)
Hip flexors	0.59	1.46	0.32 (0.20 to 0.44)	0.43 (0.28 to 0.59)
Knee extensors	0.97	1.95	0.18 (0.07 to 0.28)	0.25 (0.11 to 0.39)
Knee flexors	0.32	1.01	0.23 (0.14 to 0.33)	0.33 (0.20 to 0.46)

Note: the difference column reflects the mean difference in gait velocity between the 25th and 75th percentile for each variable. For example, all other variables being equal, participants with ankle dorsiflexor strength of 0.19 Nm/kg (75th percentile) walked on average 0.35 m/s (95% CI, 0.22 to 0.49 m/s) quicker than participants with ankle dorsiflexor strength of 0.05 Nm/kg (25th percentile).

5.4.6 Partial F-test for comparison of strength and RTD

As all measures provided significant incremental value in Table 5.9, further analysis was required to determine which measure, strength or RTD, provides the strongest relationship with gait velocity. A formal, head-to-head comparison, utilising a partial F-test, between isometric strength and RTD of the paretic side is shown in Table 5.11.

All muscle groups revealed that the RTD did not provide significant additional value in the relationship with gait velocity (both comfortable and fast) over a model that already contained isometric strength. In contrast, four muscle groups (ankle plantarflexors, hip extensors, hip flexors and knee flexors) demonstrated that isometric strength provides significant additional improvement in the relationship with comfortable gait velocity over RTD (as indicated by the significant *p*-value decrement when strength was removed from the total model and the non-significant *p*-value decrement when RTD was removed from the total model). Additionally, for fast gait velocity all muscle groups except the knee extensors had a significant improvement in their relationship with isometric strength over RTD. The results from Table 5.11 indicate that muscle strength explains a significantly higher amount of the variance in gait velocity following stroke compared with RTD.

Table 5.11. Comparison between isometric strength and rate of torque development in the association with gait velocity following stroke

	Comfortable gait velocity			Fast gait velocity		
	Total R^2	**Reduction in R^2**	***p*-value of decrement#**	**Total R^2**	**Reduction in R^2**	***p*-value of decrement#**
Ankle dorsiflexors	0.454			0.457		
Remove Strength		0.038	0.05		0.048	**0.03***
Remove RTD		0.001	0.74		0.000	0.78
Ankle plantarflexors	0.493			0.503		
Remove Strength		0.039	**0.04***		0.063	**0.01***
Remove RTD		0.002	0.68		0.000	0.98
Hip abductors	0.433			0.432		
Remove Strength		0.033	0.08		0.059	**0.02***
Remove RTD		0.021	0.15		0.012	0.28
Hip extensors	0.427			0.367		
Remove Strength		0.071	**0.03***		0.069	**0.04***
Remove RTD		0.013	0.33		0.010	0.41
Hip flexors	0.507			0.504		
Remove Strength		0.039	**0.04***		0.054	**0.02***
Remove RTD		0.007	0.37		0.005	0.48
Knee extensors	0.354			0.346		
Remove Strength		0.023	0.17		0.031	0.11
Remove RTD		0.015	0.26		0.016	0.25
Knee flexors	0.475			0.496		
Remove Strength		0.046	**0.03***		0.065	**0.01***
Remove RTD		0.000	0.91		0.002	0.71

Note: Total R^2 column reflects the total model containing the covariates (age, gender, time since stroke and country recruited) and measures of both strength and RTD for that particular muscle group. # = *p*-value of decrement is from a partial F-test evaluating the additional value of strength over RTD, adjusting for covariates, and vice versa. For example, the test for ankle plantarflexor strength and comfortable gait velocity indicates assessment of strength to provide additional value over the assessment of RTD, as shown by the significant *p*-value when strength is removed from the total model (0.04), and the non-significant *p*-value when RTD is removed from the total model (0.68); * = indicates significant *p*-value decrement when the measure is removed from the total model; RTD = rate of torque development.

5.4.7 Partial F-test for muscle group comparison

The last step in the analysis provided a head-to-head comparison to determine which lower limb muscle group had the strongest relationship with gait velocity. As strength provided a stronger relationship with gait velocity compared with RTD (as shown in Table 5.11), this step was done only with measures of strength. The muscle groups with the largest bivariate correlations from Table 5.4 and the strongest relationships from Table 5.9 were compared (ankle dorsiflexors, ankle plantarflexors, hip flexors and knee flexors) and the results are shown in Table 5.12.

The first step involved comparing ankle dorsiflexor strength with the other three muscle groups. The ankle dorsiflexors did not provide significant additional value over the other muscle groups in the association with gait velocity, and thus the ankle dorsiflexors data were removed from further analyses. The second step was to compare the knee flexors to the remaining two muscle groups (ankle plantarflexors and hip flexors). The knee flexors did not provide significant additional value over the ankle plantarflexors or hip flexors in the association with gait velocity and were removed from further analysis. The ankle plantarflexors and hip flexors were the last two muscle groups to compare, with the partial F-test demonstrating both are able to provide significant additional value over each other in the association with gait velocity. Therefore, the strength of the ankle plantarflexors and hip flexors provide the strongest relationship with gait velocity following stroke, after adjusting for covariates.

Table 5.12. Comparison between the isometric strength of four lower limb muscle groups for the relationship with gait velocity

	Comfortable Gait Velocity			Fast Gait Velocity		
	Total R^2	**Reduction in R^2**	***p*-value of decrement#**	**Total R^2**	**Reduction in R^2**	***p*-value of decrement#**
ADF vs APF	0.504			0.518		
Remove APF		0.051	**0.02***		0.061	**0.01***
Remove ADF		0.013	0.23		0.015	0.19
ADF vs HF	0.526			0.535		
Remove HF		0.073	**0.01***		0.078	**< 0.01***
Remove ADF		0.026	0.08		0.036	**0.04***
ADF vs KF	0.492			0.511		
Remove KF		0.039	**0.04***		0.054	**0.02***
Remove ADF		0.017	0.17		0.017	0.17
ADF did not provide significant additional value over APF, HF and HF for 5/6 partial F-tests						
KF vs APF	0.521			0.544		
Remove APF		0.046	**0.02***		0.050	**0.02***
Remove KF		0.030	0.07		0.041	**0.03***
KF vs HF	0.518			0.532		
Remove HF		0.043	**0.03***		0.038	**0.04***
Remove KF		0.018	0.15		0.033	0.05
KF did not provide significant additional value over APF and HF for 3/4 partial F-tests						
APF vs HF	0.542			0.556		
Remove HF		0.051	**0.02***		0.053	**0.01***
Remove APF		0.042	**0.03***		0.057	**0.01***
Both APF and HF demonstrate significant additional value over each other, no statistical difference can be observed between the two muscle groups						

Note: Total R^2 column reflects the total model containing the covariates (age, gender, time since stroke and country recruited) and measures of strength for both muscle groups. # = *p*-value of decrement is from a partial F-test evaluating the additional value of one muscle over the other, adjusting for covariates, and vice versa. For example, the first test comparing ADF and APF strength for comfortable gait velocity indicates APF strength to provide additional value over ADF strength as shown by the significant *p*-value when APF strength is removed from the total model (0.02) and the non-significant *p*-value when ADF strength is removed from the total model (0.23); * = indicates significant *p*-value decrement when the muscle group is removed from the model; ADF = ankle dorsiflexors; APF = ankle plantarflexors; HF = hip flexors; KF = knee flexors.

5.5 Discussion

This study included a multi-centre, international cohort and provided a detailed analysis on the relationship between gait velocity and isometric strength and RTD, measured with HHD, following stroke. The strength and RTD of seven lower limb muscle groups were assessed, with all variables of the paretic and non-paretic limb showing good to excellent test-retest reliability (ICC $\geq$ 0.82). All measures showed significant weak to strong relationships with gait velocity following stroke, after adjusting for covariates. Results from a partial F-test demonstrated that isometric strength provides significant incremental value over RTD in the relationship with gait velocity. Comparison of the seven lower limb muscle groups demonstrated that the strength of the ankle plantarflexors and hip flexors explain the most variance in gait velocity after stroke. Taken together, these results show that: 1) HHD measurements of strength and RTD in the stroke population are reliable; 2) isometric strength should be used as an outcome measure over RTD when considering the relationship between muscle function and gait velocity; 3) results of the bivariate correlations show the ankle dorsiflexors, ankle plantarflexors and knee flexors had a strong association with gait velocity (rho = 0.62 to 0.72); and 4) after adjusting for pertinent covariates (age, gender, time since stroke and country recruited), the ankle plantarflexors and hip flexors demonstrated the strongest relationship with gait velocity of the seven lower limb muscle groups assessed in this study.

Results of the reliability analysis revealed good to excellent test-retest reliability for measures of isometric strength and RTD measured with a HHD in the stroke population across all seven lower limb muscle groups assessed (ICC = 0.82 to 0.97). This is the first study to examine the reliability of the measurement of RTD using HHD in a stroke cohort. Limited previous research has examined test-retest reliability of HHD (between sessions) in

neurological populations for measurement of lower limb isometric strength; those that have been published included small sample sizes and reported mixed results (Morris et al., 2008; Riddle et al., 1989). Other studies have reported within-session reliability in stroke populations, also with small sample sizes (Bohannon, 1986b, 1989a). Analysis of measures between sessions potentially provides more useful information on the reliability of HHDs, as assessment over time is relevant to clinical practice. One previous study of 15 participants following either stroke or a closed head injury measured the paretic and non-paretic ankle dorsiflexors, hip flexors, knee extensors and knee flexors and demonstrated similar test-retest reliability to the current study for the paretic limb (ICC = 0.87 to 0.98) (Riddle et al., 1989). However, the non-paretic limb showed lower results for test-retest reliability compared to the results of the current study (ICC = 0.56 to 0.91) (Riddle et al., 1989). Another study of 10 participants with traumatic brain injury reported much larger variance in the reliability statistics compared to the current study with moderate to excellent test-retest reliability of the paretic ankle plantarflexors, hip flexors and knee extensors (ICC = 0.55 to 0.93), with even lower reliability on the non-paretic side (ICC = 0.09 to 0.86) (Morris et al., 2008). Lower test-retest reliability results of the non-paretic limb compared with the paretic limb were also shown in the current study but to a much lesser extent. The lower reliability for the non-paretic side may be in part due to greater strength on the non-paretic side resulting in difficulties for the assessor to match the force of the participant. Another possible explanation for the lower reliability on the non-paretic side is the potentially greater heterogeneity between participants on the paretic side. Nonetheless, the current study revealed good to excellent reliability (ICC = 0.82 to 0.97) for both strength and RTD across seven lower limb muscle groups for both sides, indicating the potential for future use of HHD for the measurement of isometric strength and RTD in the stroke population.

Closer examination of the SEM and MDC values demonstrated higher SEM and MDC for isometric RTD compared with isometric strength (similar to Study Two in a healthy cohort). The SEM for isometric strength ranged from 6 to 13% of the mean and for isometric RTD ranged from 10 to 22% of the mean. Although RTD had higher SEM values, both measures provided somewhat low values indicating acceptable response stability. The current study also revealed quite mixed MDC values (range of 18 to 60% of the mean), which could potentially limit the usefulness of HHD in the stroke population for detecting change over time. However, when examining differences in MDC between the measures of isometric strength and RTD, the strength measures ranged from 18 to 36%, whilst RTD ranged from 27 to 60%. This indicates that caution is needed with measures of RTD from HHD in the stroke population as a large change in RFD is required to be confident of a true change in RFD levels. This could be problematic for clinicians using HHD for assessment of RTD during rehabilitation after stroke. The higher MDC values for RTD may also potentially explain the lower associations between RTD and gait velocity compared with strength measures. Despite the strong reliability results for RTD taken from HHD, measurements of RTD may need to be performed using laboratory-based fixed dynamometry, although further research is required in the stroke population.

The results of the bivariate analysis demonstrated the ankle dorsiflexors, ankle plantarflexors and knee flexors have strong correlations with gait velocity following stroke. All associations for the non-paretic side were very weak or weak (rho = 0.03 to 0.24, $p > 0.05$), suggesting that gait velocity is inhibited by the paretic limb strength. It appears that increasing non-paretic strength would have little effect on gait velocity, although strength training interventions are rarely focused on one limb and especially not solely focused on the non-paretic limb during stroke rehabilitation. Limited previous research exists that has examined the bivariate associations between strength and gait velocity in multiple lower

limb muscle groups of the paretic side (Mentiplay et al., 2015a). Instead, many articles focus on one or two muscle groups which makes comparison between muscle groups difficult. Only one study identified in Study One has examined more than two lower limb muscle groups (a total of 12 lower limb muscle groups were examined) with a sample size above 40 (Dorsch et al., 2012). The study by Dorsch et al. (2012) found that ankle dorsiflexor strength had the largest bivariate association with gait velocity following stroke. The current study also demonstrated that the ankle dorsiflexors had a strong bivariate correlation with gait velocity, as well as the ankle plantarflexors and knee flexors. The studies identified in the systematic review showed only weak to moderate correlations for ankle plantarflexor strength, despite the importance of this muscle group for forward progression during gait (Liu et al., 2006; Olney et al., 1991). This may be in part due to the strength assessment protocol used in previous studies, with the lower limb positions not reflective of those seen during gait, which could potentially reduce the effects of ankle plantarflexor strength on gait (e.g. hip and knee in 90° of flexion as per the protocol used by Dorsch et al. (2012)). Interestingly, as can be seen in Figure 5.2, the current study showed a trend towards stronger bivariate associations between isometric strength and gait velocity across all muscle groups compared with the studies identified in Study One that also included a relatively large sample size. However, caution is needed when comparing the current study to previous studies due to the differences in the methods employed (e.g. different dynamometers, assessors and participant positions used for strength assessment as well as different statistics with either Spearman's or Pearson's correlations).

After examining the results of the multivariable regression analyses and partial F-tests, the strength of the ankle plantarflexors and hip flexors were shown to explain the highest amount of variance in comfortable and fast gait velocity (ankle plantarflexor total R^2 = 0.491 and 0.503; ankle plantarflexor R^2 increment = 0.291 and 0.346; hip flexor total R^2 = 0.500 and

0.499; hip flexor R^2 increment = 0.299 and 0.342), which highlights the importance of these muscle groups when considering gait velocity after stroke. Interestingly, hip flexor strength only showed a moderate bivariate association with gait velocity (rho = 0.53 and 0.56) but demonstrated the largest R^2 in the multivariate regression models. This may indicate that the other muscle groups are more affected by the covariates within the regression model compared with the hip flexors, although further research is required to examine how age, gender, time since stroke or country of residence affects the relationship between strength and gait velocity following stroke. Nonetheless, the strength of the ankle plantarflexors and hip flexors may be the key muscle groups when considering gait velocity as they explained approximately 49-50% of the variance in gait velocity for both comfortable and fast paced gait with covariates included. This result is not surprising, as the ankle plantarflexors and hip flexors provide two of the major power generation events for forward propulsion during gait (Kepple et al., 1997; Liu et al., 2006; Neptune et al., 2004). The results from this study could help to inform targeted interventions that focus on training the ankle plantarflexors and hip flexors with the aim of improving gait velocity following stroke.

The strength of the ankle dorsiflexors and knee flexors showed strong bivariate correlations with gait velocity following stroke. The ankle dorsiflexors have shown strong associations with gait velocity in previous studies with large sample sizes and adequate methodological quality (Mentiplay et al., 2015a). Although the ankle dorsiflexors do not contribute to ankle joint power generation during gait, they do assist to clear the foot during the swing phase of gait (Whittle, 2002; Winter, 1991). Inadequate ankle dorsiflexion during swing may lead to compensatory strategies such as hip hiking or leg circumduction, which could potentially reduce gait velocity (Dorsch et al., 2012). The ankle dorsiflexors and knee flexors showed strong bivariate correlations compared to other lower limb muscle groups, however in the multivariate regression models, the ankle plantarflexors and hip flexors showed the strongest

relationship with gait velocity. This may indicate that the ankle dorsiflexors and knee flexors were more affected by the covariates (e.g. time since stroke or age) in the model compared with other muscle groups.

It is interesting to note that this study showed a strong correlation between the lower limb flexor muscle groups (ankle dorsiflexors, knee flexors and hip flexors) and gait velocity, as has been demonstrated previously (Dorsch et al., 2012). This may potentially be explained by the higher functional abilities of the participants included in this study, as well as the previous study by Dorsch et al. (2012), who were all able to walk without the use of assistive devices. The participants would have required sufficient strength in the lower limb extensor muscle groups to create an overall extensor moment to prevent collapse of the limb during the stance phase of gait (Dorsch et al., 2012), which is a requirement of independent gait (Bohannon & Eriksrud, 2001; Winter, 1980). As the participants had enough strength to support their lower limb during stance, the strength of the flexor muscle groups may be more important to produce an efficient swing phase that would potentially result in an increased gait velocity (Dorsch et al., 2012). Increased hip and knee flexion would have an impact on the rotational inertia about the hip joint centre, with more flexion causing the centre of mass to be closer to the joint centre which would therefore make it easier to swing the leg through faster. As such, training the strength of the lower limb flexor muscle groups (ankle dorsiflexors, knee flexors and hip flexors) may also need to be considered during stroke rehabilitation.

The hip abductors, hip extensors and knee extensors showed moderate associations with gait velocity. Knee extensor strength is commonly assessed in neurological populations, with the current study adding to the results of Study One, suggesting that the knee extensors play a limited role in gait velocity due to the lower correlation values compared with other muscle

groups. The hip abductors do not act in the sagittal plane and whilst they provide stabilisation in the mediolateral axis during gait (Winter, 1995), they may not necessarily have a large contribution to gait velocity, as evidenced by the lower correlation values reported in the current study. Interestingly, hip abductor strength showed a strong correlation with gait velocity in the Australian cohort compared with the moderate correlation for the entire cohort. However, a full comparison between the Australian and Singaporean cohorts was problematic due to the relatively small sample size of the Australian cohort (n = 22), even though the Australian cohort was larger than 12/21 studies identified in the systematic review in Study One. The hip extensors contribute to hip power generation during gait to produce a burst of power just after ground contact (Liu et al., 2006; Neptune et al., 2004) and as such the moderate correlation values were unexpected. This could potentially be a result of the testing protocol, with the participant in a prone position that results in the participant working against gravity and therefore not reflective of the muscle actions during gait. Only 50/63 participants completed the hip extensor testing due to other complications that limited some participants' ability to be in a prone position (17/22 Australian participants and 33/41 Singaporean participants). As such, the regression model of the covariates for hip extensors had a larger base model R^2 (0.281 and 0.211 for hip extensors compared with 0.201 and 0.157 when all participants were included for comfortable and fast gait velocity respectively). This would limit the R^2 increment of the hip extensors over the base model, potentially biasing the multivariate regression models. However, the total model R^2 for the hip extensors was still lower than most muscle groups indicating that the measurement of hip extensor strength and RTD (as performed in this study) may not be as important for gait velocity as other lower limb muscle groups. Other assessment protocols for hip extensor strength that reflect the hip joint position seen during gait may improve the relationship with gait velocity.

Another interesting finding of the current study was that measures of RTD did not provide any significant incremental improvement in the relationship with gait velocity over isometric strength. Although the RTD of all muscle groups had a significant relationship with gait velocity after stroke, isometric strength appears to provide incremental value over and above RTD in the association with gait velocity. This is quite interesting when considering the results of this study also showed a strong correlation between the measures of isometric strength and RTD (rho = 0.80 to 0.94 across the lower limb muscle groups). However, the variance in isometric strength that is unexplained by RFD is still substantial (12 to 36%) and therefore it is possible that the incremental value of strength over RTD may be attributed to this unexplained variance. The increased SEM and MDC values for the test-retest reliability of RTD, which indicate greater variability in RTD measures, may also impact on the difference in correlation values between strength and RTD in the relationship with gait velocity.

In contrast to the current study, previous research has shown RTD has a stronger relationship with various measures of physical function in a range of clinical populations (Maffiuletti et al., 2010; Moreau et al., 2012; Pohl et al., 2002; Winters et al., 2014). A previous study of 83 participants following stroke (range of 36 to 145 days since stroke), utilising similar statistical analysis techniques as the current study, found RTD provided incremental value in the relationship with gait velocity over muscle strength (Pohl et al., 2002). The regression model presented by Pohl et al. (2002) demonstrated that the knee extensors only explained 12% of the variance in gait velocity (with age and gender as covariates). The current study found that the ankle plantarflexors and hip flexors explain 49-50% of the variance in gait velocity (with age, gender, time since stroke and country recruited as covariates). This contrast may be explained by the previous study by Pohl et al. (2002) only measuring the strength and RTD of the knee extensors, a muscle group that has little impact upon gait

velocity as can be seen from the systematic review in Study One as well as the results of the current study, with both demonstrating that knee extensor strength has a weak association with gait velocity.

Another limitation of the previous study by Pohl et al. (2002) was that the gait velocity of participants was assessed whilst using their usual assistive devices (57 out of 83 participants used an assistive device with 15 using an ankle foot orthosis) (Pohl et al., 2002). The current study required participants to walk barefoot without any assistive devices, even if assistive devices were usually used, to ensure all participants were assessed in an equal manner. The use of assistive devices can change the muscle actions during gait and thus can alter the relationship between strength and gait velocity. The study by Pohl et al. (2002) had many differences with the current study in that they used a fixed, laboratory-based dynamometer to measure isometric muscle function, used a different method of RTD calculation that involved a linear fit, had participants with a shorter time since stroke, allowed the use of assistive devices during gait assessment and assessed only one muscle group. These methodological differences may explain the discrepancy in the importance of RTD over strength when examining the relationship with gait velocity following stroke.

5.5.1 Limitations

It is acknowledged that correlations do not indicate causation and therefore improvements in muscle strength or power may not necessarily result in improvements in gait velocity following stroke. Intervention-based studies or randomised controlled trials are needed to make such assertions, nevertheless, the study of associations is still warranted. The current study can be used to guide future intervention programs where facilitating the improvement of gait velocity is a goal of the intervention by potentially shifting the focus of clinicians from the knee extensors to improving ankle plantarflexor and hip flexor strength.

Additionally, a stronger relationship between isometric strength and gait velocity does not indicate that interventions to improve muscle strength would provide larger gains in gait velocity compared with interventions to improve RTD. Future interventional studies are needed to examine whether conventional strength training or power-based, ballistic training provides greater improvements in physical function following stroke and which muscle groups should be trained in order to see optimal improvement in gait velocity after stroke. Future research using longitudinal study designs could also examine the correlation between improvements in gait velocity and lower limb muscle strength as well as the responsiveness of HHD measures.

The current study demonstrated that across all muscle groups, measurement of muscle strength accounts for a larger explanation of the variance in gait velocity compared with RTD. Therefore, in the stroke population, strength measurements obtained from HHD can be used without the need to post-process raw data to obtain measurements of RTD. Other measures of dynamic power (using equipment such as string potentiometers or force plates) may have a stronger relationship with gait velocity after stroke. Evidence suggests that dynamic measures of muscle power using pneumatic resistance machines may explain more of the variance in gait velocity compared with muscle strength in a range of populations, including those with Parkinson's and mobility limited older people (Allen, Sherrington, Canning, & Fung, 2010; Bean et al., 2002; Cuoco et al., 2004; Sayers, Guralnik, Thombs, & Fielding, 2005). Future work is still needed in the stroke population to determine if measures of dynamic power have a stronger relationship with gait velocity over conventional measures of muscle strength.

The protocol for assessment of isometric strength and RTD used in the current study has limitations. The low sampling rate of the HHD used in the current study (40Hz) may be

unable to accurately measure the quick and forceful rise in force. The additional foam padding used on the HHD (shown in Figure 5.1) may have also potentially attenuated some of the initial rapid rise in force. However, the used of peak RTD should overcome this limitation (in comparison to an averaged measurement or a measurement based on the onset of contraction), and the foam padding was crucial to minimise discomfort during testing in the stroke cohort.

Despite the strong reliability results for isometric ankle plantarflexor strength and RTD shown in this thesis for both unimpaired and stroke cohorts, the concurrent validity of the ankle muscle groups shown in Study Two (Section 4.4), when compared with a laboratory-based dynamometer, were less than favourable for the ankle. The poor to moderate validity results may be in part due to the ankle attachment used on the criterion reference isokinetic dynamometer (as discussed in Study Two), but the results from Study Two still need to be considered and further research is needed. It could be stated that measurement of ankle plantarflexor strength and RTD, despite the lower concurrent validity results, has demonstrated acceptable face validity due to the strong association with gait velocity shown in the current study. These two measures of muscle function and gait velocity should logically demonstrate a strong relationship due to the importance of the ankle plantarflexors in producing forward progression during gait following stroke (Olney et al., 1991) and thus this study may show good face validity of ankle plantarflexor strength and RTD measures.

Another potential limitation of the strength assessment protocol is that the joint angles used during testing do not reflect the joint angles seen during walking for some muscle groups assessed. For example, the hip flexors were tested at 90 degrees of hip flexion, whereas previous studies in the stroke population have reported that the hip goes through a range from around 18 to 25 degrees of hip flexion to 4 to 13 degrees of hip extension when walking

(Olney & Richards, 1996). Furthermore, the isometric nature of assessment also does not necessarily represent the dynamic muscle contractions that occur during walking. Nonetheless, HHD is one of the most clinically feasible devices for the assessment of isometric strength and RTD due to the minimal equipment requirements, relatively inexpensive purchase price, limited participant position changes and low time demands of testing. The protocol used in this thesis is reliable (as shown in the current study and Study Two, Section 4.3) and provides a quick and easy assessment of muscle strength. The investigation of RTD using a clinically feasible device such as HHD was warranted in the current study. Future research could examine measures of muscle strength or power that better represent the positions and actions of the muscles seen during gait. The findings of such research may provide a stronger link between the functions of the lower limb muscles and gait velocity after stroke.

Other factors that could potentially affect the relationship between strength/RTD and gait velocity include the presence of lower limb spasticity or proprioceptive deficits. These impairments were not assessed, nor were participants excluded if these impairments were present, which may have influenced the results of this study. Future research could examine how other factors, such as spasticity, impact upon the relationship between strength/RTD and gait velocity following stroke. However, results from Study One suggest that spasticity may not necessarily affect the relationship between muscle strength and gait following stroke. Another potential for future research is to examine non-linear relationships between isometric strength and gait velocity to determine how the relationship changes in those with varying levels of muscle strength.

Potential differences in the correlations between gait velocity and strength/RTD depending on the country recruited and the time since stroke of the participants were observed in the

secondary analyses presented in Section 5.4.4. Consequently, all multivariate analyses included both country and time since stroke as covariates. One example is the differing correlation results for hip abductor strength between the Australian and Singaporean cohort. Another example is the lower correlation values for those who were less than one year following stroke. Lower limb muscle strength may be less important for determining gait velocity in the first year following stroke, with other factors potentially impacting upon gait velocity. Further research is required to determine how this association changes throughout the recovery period after stroke. The differences between the country of recruitment and the time since stroke needs further investigation, as the relatively small sample sizes in each group (e.g. 22 participants from Australia) prevent a comprehensive analysis from being undertaken.

The current study only assessed one aspect of gait function, gait velocity, as it has strong reliability (Flansbjer et al., 2005) and provides a good indication of the overall level of functional mobility after stroke (Salbach et al., 2001; van de Port, Kwakkel, & Lindeman, 2008). Other variables of gait function, such as the Six Minute Walk Test or spatiotemporal gait variables, are also potentially important. The RTD may provide a stronger association with other measures of gait function compared to muscle strength, although further investigation is required.

5.6 Conclusion

This study revealed that HHD measurements of lower limb isometric muscle strength and RTD are reliable in the stroke population. Both measures of muscle strength and RTD demonstrated significant associations with gait velocity following stroke. However, comparison of the two measures demonstrated muscle strength to explain more of the variance in gait velocity over and above measures of RTD. The strength of the ankle

plantarflexors and hip flexors demonstrated the largest relationship with gait velocity and provided significant incremental value over the other muscle groups in explaining the variance in gait velocity following stroke, after adjusting for covariates.

This study is one of the largest studies examining the relationship between strength and gait velocity after stroke, with a sample size of 63. Many studies that have previously examined the relationship between strength and gait velocity have included relatively small sample sizes of less than 30 (13/21 studies identified in Study One). Only one study identified in the systematic review in Study One assessed the isometric muscle strength of multiple lower limb muscle groups and had a relatively large sample size of 60 (Dorsch et al., 2012). The current study adds a large, international study to the results of the systematic review in Study One as well as examined isometric RTD, a measure that has rarely been assessed in the stroke population. The results also provide support for the potential emphasis of ankle plantarflexor and hip flexor strength in future research focused on gait velocity outcomes. The majority of prior studies have assessed knee extensor strength, which may not be as relevant to gait velocity following stroke.

With respect to the implications of this study, there needs to be an established, simple method for the assessment of ankle plantarflexor and hip flexor strength that can be used routinely in the clinical setting. The HHD used in the current study is a relatively inexpensive option that can be used quickly and easily, although it is not without limitations as have been discussed in previous chapters. A fixed dynamometer rig may improve the validity of ankle strength and RTD measurements, however a commercially available device was chosen for this thesis to enable wide-spread replication as well as application of the results in a clinical setting.

CHAPTER SIX: ASSOCIATIONS OF LOWER LIMB STRENGTH AND POWER WITH JOINT POWER GENERATION FOLLOWING STROKE (STUDY FOUR)

6.1 Preamble

An important aspect of gait function is the joint power generated throughout the gait cycle (Brincks & Nielsen, 2012; Kim & Eng, 2004; Olney et al., 1994; Olney et al., 1991). Despite this importance, the expensive equipment, technical expertise and time required to assess power generation during gait limits the ability for routine clinical assessment. Therefore, clinical-based assessments that help explain the variance in joint power generation would be useful during rehabilitation. Study Two and Three of this thesis have demonstrated the ability of HHD to assess isometric muscle strength and power in both unimpaired and stroke cohorts. Despite Study Three demonstrating isometric strength to have a stronger relationship over isometric power with gait velocity (Study Three and Four were performed concurrently), measures of the RTD may still provide additional value in the relationship when considering joint power generation. Therefore, the aim of this study (Study Four) was to assess the relationships between HHD measures of isometric strength and RTD with joint power generation during gait following stroke.

6.2 Introduction

Stroke is a leading cause of disability worldwide (Adamson et al., 2004) and often results in reduced gait function (Olney & Richards, 1996). One of the main goals of rehabilitation

following stroke is to regain the ability to walk independently (Kwakkel & Kollen, 2013). Walking ability, in particular walking speed, can be predictive of community ambulation and has been associated with levels of physical activity after stroke (Lord et al., 2004; Mudge & Stott, 2009; Perry et al., 1995). Identifying how and which lower limb muscle groups act during gait can aid clinicians during stroke rehabilitation to use specific and targeted interventions to potentially improve gait function.

Studies have shown that the primary muscle group contributing to gait are the ankle plantarflexors, and that peak APG is the main component to produce forward progression during gait (Liu et al., 2006; Olney et al., 1991). The peak APG during gait occurs in the push-off phase of the gait cycle where the plantarflexors produce a quick and forceful contraction to propel the lower limb forward. Deficits in APG can impede the ability to achieve normal gait speeds, with studies showing strong correlations between APG and gait velocity in the stroke population (Olney et al., 1994; Olney et al., 1991). The hip flexors and hip extensors have also been reported as key muscle groups for generating power during gait (Liu et al., 2006; Neptune et al., 2004). Previous studies have shown that increases in gait velocity following intervention have coincided with higher levels of joint power generation at the ankle and hip (Brincks & Nielsen, 2012; Teixeira-Salmela et al., 2001), highlighting the potential importance of joint power generation in stroke rehabilitation. However, the assessment of joint power generation involves 3DGA with integrated force platforms. Such systems are expensive, require technical expertise and are time consuming, which limits the ability for routine and regular assessment of joint power generation in a clinical setting. Therefore, the identification of clinically feasible measures that have a strong relationship with joint power generation may be beneficial to clinicians.

Measures of muscle strength are often used to provide an indication of function following stroke (Canning et al., 2004). The peak force a muscle can produce (muscle strength) is associated with walking ability following stroke (Flansbjer et al., 2006; Lin et al., 2006) and can be measured quickly and easily using HHD as demonstrated in Study Two and Three. It may be pertinent to examine the relationship between measures of isometric muscle strength using a clinically feasible device and joint power generation. Two previous studies have examined this relationship in other neurological populations (Dallmeijer et al., 2011; Kahn & Williams, 2015). One of these studies in those following traumatic brain injury examined the relationship between isometric ankle plantarflexor strength measured with HHD and APG and found a significant moderate correlation ($r = 0.43$) (Kahn & Williams, 2015). However, this study did not report the reliability of the strength assessor, which is particularly important with HHD, and did not normalise the strength values to body mass (Kahn & Williams, 2015). Another study of people with bilateral spastic cerebral palsy examined the associations between HHD measures of strength and joint power generation (Dallmeijer et al., 2011). This study also reported significant moderate correlations between ankle plantarflexor strength and peak APG ($r = 0.57$ and 0.41 for the left and right leg respectively) (Dallmeijer et al., 2011). Despite these previous studies in other neurological populations, the relationship between isometric strength and joint power generation during gait has not been examined in the stroke population. Isometric muscle strength is just one component of muscular function, with isometric muscle power being another aspect that may provide a stronger association with joint power generation.

Measures of isometric muscle power have previously been quantified by calculating the RTD, which is determined as the change in torque (or force) over change in time during the initial rise in an isometric contraction (Aagaard et al., 2002). As both measures of RTD and joint power generation are dependent on time, the relationship between HHD measures and

joint power generation may be improved through the calculation of RTD (compared to isometric strength). Evidence suggests that the measure of RTD is important in different clinical populations such as cerebral palsy and knee osteoarthritis (Moreau et al., 2012; Winters & Rudolph, 2014). Following stroke, RTD is reduced on the paretic compared to the non-paretic side (Fimland et al., 2011) and may provide additional value in the relationship with gait velocity compared with isometric strength (Pohl et al., 2002), despite the conflicting results reported in Study Three (Study Three and Four were run concurrently, with the results of Study Three not yet determined). Study Two and Three examined the psychometric properties of HHD for assessment of RTD in healthy and stroke cohorts, and demonstrated acceptable reliability and validity for the measure of RTD. The calculation of RTD using HHD may provide a suitable, clinically feasible alternative for assessing joint power generation during the gait cycle that can be used for routine patient assessment.

Therefore, the overall aim of the current study was to determine the relationships between HHD measures of isometric strength and RTD with joint power generation following stroke. Specific aims were to: 1) examine the relationship between peak ankle, knee and hip joint power generation during gait with corresponding ankle, knee and hip joint measures of isometric strength and RTD as measured using HHD; and 2) to determine which measure, either isometric strength or RTD, provide a stronger association with joint power generation following stroke.

6.3 Methods

6.3.1 Participants

A convenience sample of adults who were 21 years or older were recruited from outpatient physiotherapy and rehabilitation clinics at two major hospitals in Australia and Singapore.

The participants included in the current study were a subset of those participants who were enrolled in Study Three. Participants from Study Three who were willing and able to attend an assessment in a 3DGA laboratory were recruited for this study.

Selection criteria were kept consistent with Study Three. Briefly, the inclusion criteria involved patients who were at least three months following stroke to ensure the patients had the ability to perform the 3DGA with no physical assistance and minimal supervision. Participants were also required to be able to walk barefoot during gait assessment without any assistive devices (e.g. canes or ankle foot orthoses), even if it was usual for them to use aids for longer distances. Exclusion criteria were cerebellar stroke due to the different clinical presentation of such strokes (e.g. gait ataxia) (Edlow et al., 2008; Kase et al., 1993; Tohgi et al., 1993), any cognitive issues where the participant was unable to follow instruction as indicated by a score below seven on the Abbreviated Mental Test Score (Hodkinson, 1972) or other diagnosed medical comorbidities such as cardiac problems that would preclude or alter participation in tests of muscle function and gait.

A power calculation was performed in accordance with Hulley, Cummings, Browner, Grady, and Newman (2013) for a correlation study with 80% power, a one-tailed alpha and an expected moderate association (r-value of 0.47), based on the average of previously reported correlation values in other neurological populations (Dallmeijer et al., 2011; Kahn & Williams, 2015), 27 participants were required.

6.3.2 Procedure

Data collection for this study had ethical approval from the relevant ethics committees at each hospital in Australia and Singapore as well as registration through the Australian Catholic University (see Appendix H). All participants provided written informed consent prior to study enrolment. Characteristics collected from participants included age, gender,

race, height and weight. Pertinent stroke details were also collected including time since stroke, paretic side (left or right), type of stroke (ischaemic or haemorrhage) and assistive devices normally used when ambulating outdoors. A cross-sectional, observational design was used for the current study whereby participants attended one session in a 3DGA laboratory for assessment of joint power generation and isometric muscle strength and RTD. All procedures were kept consistent across laboratories and the same assessor (thesis author BFM) performed all tests of joint power generation (including marker placement) and isometric strength and RTD in Australia and Singapore. At both sites, the 3DGA was performed first followed by assessment of isometric muscle function.

6.3.3 Three-dimensional gait analysis

Two 3DGA laboratories were used for data collection in this study, with one in Australia and one in Singapore. The Australian laboratory contained a nine camera Vicon system sampling at 100Hz (Vicon, Oxford, UK) and an embedded AMTI OR6 Series force platform sampling at 1000Hz (AMTI, Watertown, MA USA), with data collected in Vicon Nexus software version 1.8.5. The Singaporean laboratory contained a ten camera Qualysis system sampling at 200Hz (Qualysis, Gothenburg, Sweden) and an embedded Kistler 9260AA6 force platform sampling at 1000Hz (Kistler, Winterthur, Switzerland), with data collected in Qualysis Track Manager software version 2.12. The two laboratories used in the current study had equipment from different manufacturers. Previous research has examined the reliability of kinematic and kinetic data across three laboratories with different equipment for an athletic population performing dynamic jumping manoeuvres (Myer et al., 2015). Despite the coefficient of multiple correlations showing acceptable reliability, the absolute outcome measures appeared to provide differing results across laboratories (Myer et al., 2015). Different assessors were used at each site to perform the marker placements, which

may have resulted in the differing results across the laboratories (Myer et al., 2015). The current study had the same assessor performing all marker placements across Australia and Singapore (thesis author BFM), however, assessing the inter-laboratory reliability across laboratories in the current study was impractical due to international design of the study. Instead, all regression models were adjusted for the country of recruitment to control for any discrepancies between laboratories.

Participants performed all trials barefoot without any assistive devices. Trials involved the participants walking from one side of the laboratory to the other with the force platform in the middle of the walkway. Data were recorded only when the participants walked in one consistent direction, to reduce the potential for erroneous kinetic data with participants walking in different directions. A series of walking trials were collected under two self-selected conditions: 1) at a comfortable pace; and 2) at a fast pace. Instructions to participants were to walk at a comfortable pace across the laboratory for the first condition and to walk as fast as safely possible, without running, across the laboratory for the second condition. As the stroke population is susceptible to fatigue, rests and water breaks were given when necessary. The total number of trials performed by the participant was dependent on obtaining an adequate number of successful trials. Trials were deemed successful when a clear foot placement on the force platform was visually observed by the assessor. The starting position of the participant was altered by the researchers to encourage a clear foot placement on the force platform, with the participants unaware of the force platform during testing. Successful trials were captured on both limbs with five successful trials ideally recorded for each walking condition.

The marker set used for data collection was a cluster-based lower limb marker set similar to the marker set used by Collins, Ghoussayni, Ewins, and Kent (2009). Participants had

reflective markers placed on their pelvis, thighs, shanks and feet. A minimum of four tracking markers were placed on each segment, with the model requiring a minimum of three markers on each segment being visible throughout the entire walking trial to recreate the position of the segments. Markers were placed directly on the skin with double-sided tape and reinforced with stretch tape. The same assessor performed all marker placements and captured the data across both laboratories (thesis author BFM). A static trial was captured prior to the walking trials to allow for static calibration of the participant to the model, which was also consistent for data between both laboratories.

The pelvic model used in this thesis was a CODA model with two additional markers used for tracking during the dynamic trials. During the static trial, the hip joint centres were based off previously reported CODA equations (Bell, Brand, & Pedersen, 1989; Bell, Pedersen, & Brand, 1990). The majority of pelvic models only require four markers (anterior and posterior superior iliac spine markers), however the additional pelvic markers were used in this study due to the potential issue of marker occlusion in those participants with more weight around their pelvis or in those participants with upper limb impairment (e.g. spasticity), which can often occlude the anterior superior iliac spine markers during walking. The model requires a minimum of three markers per segment to be visible throughout the trials and therefore it was decided to include two additional tracking markers on the iliac crest (Collins et al., 2009; Wilken, Rodriguez, Brawner, & Darter, 2012).

During the static trial, the knee joint centre was defined as the midpoint between the lateral and medial epicondyle markers and the ankle joint centre as the midpoint between the lateral and medial malleoli markers, as has been used previously (Besier, Sturnieks, Alderson, & Lloyd, 2003; Cappozzo, Catani, Della Croce, & Leardini, 1995; Collins et al., 2009). To track these joint centres as well as the thigh and shank segments during the walking trials, a

cluster of four markers were placed on each segment, similar to those used by Collins et al. (2009). The thigh segment was created from the hip joint centre to the knee joint centre and the shank segment from the knee joint centre to the ankle joint centre.

The foot segment involved different marker sets between Australia and Singapore. The foot segment was created exactly the same at both sites from the ankle joint centre to a virtual marker at the midpoint between the first and fifth metatarsal markers. Four tracking markers for the foot were used in both Australia and Singapore. The tracking markers used in Australia included markers placed on the calcaneus, the midfoot (two markers on the navicular and base of the 5^{th} metatarsal) and the forefoot (one marker on the space between the heads of the second and third metatarsal). The tracking markers in Singapore were placed on the calcaneus, the midfoot (one marker on the base of the second/third metatarsal) and the forefoot (two markers on the head of the first and fifth metatarsal). The same assessor (thesis author BFM) performed all gait analyses including marker placements, however the data collection in Singapore was performed in a laboratory which used the slightly different foot model and it was not possible to replicate the marker set used in Australia. As part of gaining access to use the gait laboratory in Singapore, a gait analysis report needed to be generated for each participant to provide to their physiotherapist. The slightly different foot marker placement was required to generate this gait report. The difference in the foot segment was deemed to have minimal effect on the data, as the joint definitions of the foot was kept consistent, only the markers that tracked the joint centres were altered.

Gait velocity was calculated from a virtual pelvis landmark halfway between the two posterior superior iliac spine markers. If the markers placed on the posterior superior iliac spine markers were occluded during a walking trial, the anterior superior iliac spine markers were used to calculate gait velocity. Specific anatomical details of marker placements are

provided in the appendices (see Appendix D), with a visual display of the lower limb model shown in Figure 6.1.

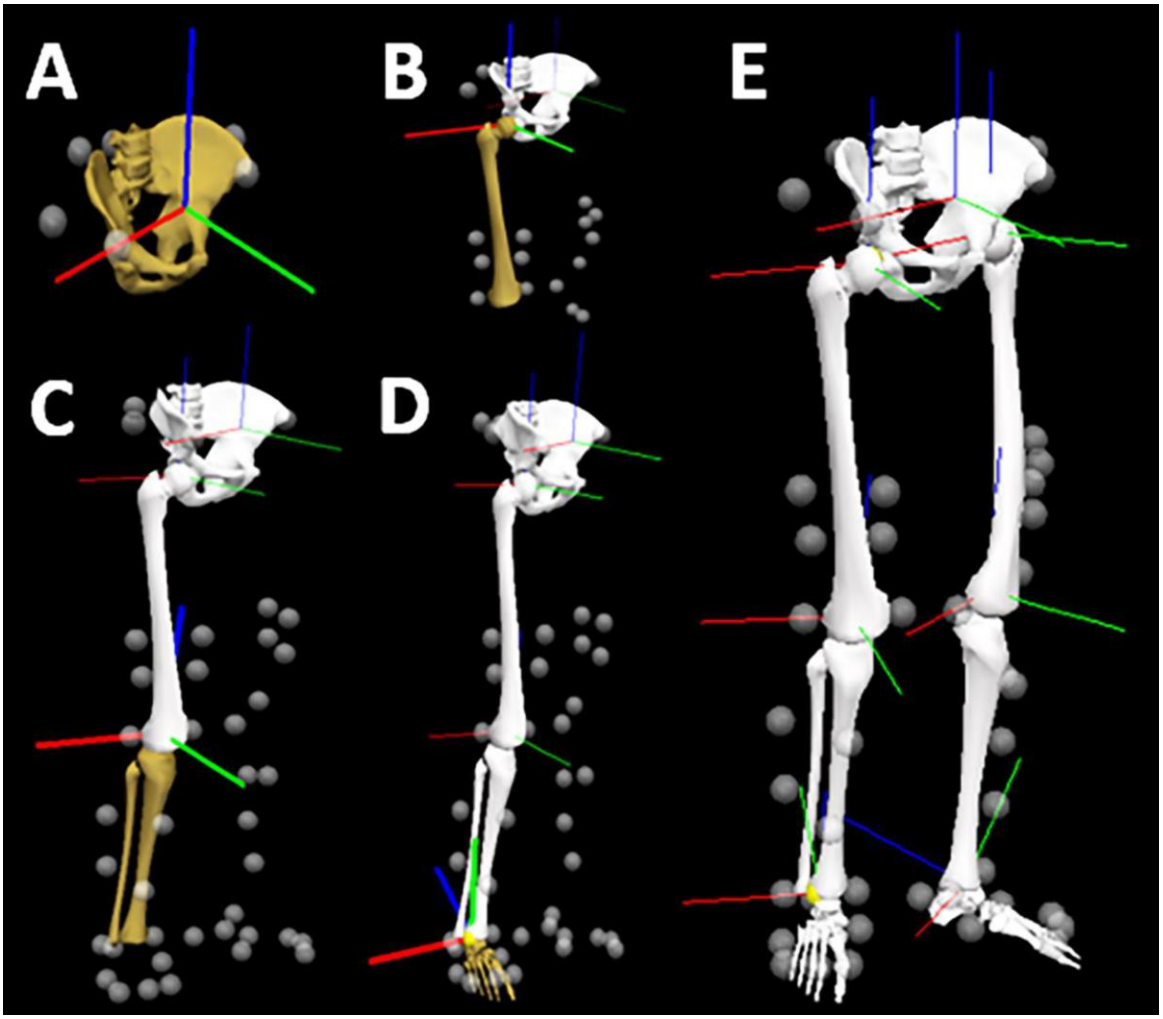

Figure 6.1. Lower limb model with markers and joint axes definitions. Blue lines are the vertical axes, red lines are the mediolateral axes and green lines are the anteroposterior axes. A = the pelvis model; B = the thigh model; C = the shank model; D = the foot model; E = the total lower limb model.

Raw marker trajectory data were cleaned using relevant software at each laboratory. Data from both laboratories were then imported to Visual3D (C-motion, Inc., Germantown, MD USA), to create the three-dimensional model, with the same model used for data from both sites. Marker trajectory data were filtered using a 10Hz lowpass Butterworth filter prior to

calculation of outcome measures, as has been performed previously (Noehren, Manal, & Davis, 2010; Parvataneni et al., 2007). The gait cycle was determined as the time between initial ground contact of one limb and the subsequent ground contact of the same limb. The first ground contact was determined from the force plate contact (the first sample recorded above 5 Newtons) and the second ground contact was defined as the next minimum in the vertical axis of the calcaneus marker after the force plate ground contact of the same limb. Some participants walked with a forefoot landing, in contrast with a heel strike, and in this instance, visual observation of the walking trials was used to determine the second initial contact.

The primary gait variables of interest for the current study came from the sagittal plane joint power generation across the gait cycle in the ankle, knee and hip joints. Only sagittal plane power was examined as the majority of the power generated throughout the gait cycle occurs in this plane (Eng & Winter, 1995). Additionally, sagittal plane joint power provides a stronger relationship with gait velocity following stroke compared with frontal or transverse plane measures of joint power (Kim & Eng, 2004). A standard inverse dynamics approach was used to calculate net joint moments, with the moments then multiplied by joint angular velocity to calculate net joint power generation (in Watts) during the gait cycle (Winter, 1983). To allow comparison between participants, joint power was normalised to body mass (W/kg). Normalised joint power generation was then filtered with a 15Hz lowpass Butterworth filter, similar to previous research that has filtered kinetic data (Beaulieu, Lamontagne, & Beaulé, 2010; Parvataneni et al., 2007; Zeni Jr, Richards, & Higginson, 2008). Figure 6.2 shows the four primary variables used in this study, which are the peak power generation events at each joint. These peak power events are commonly used when examining joint power generation after stroke (Brincks & Nielsen, 2012; Jonkers et al., 2009; Kim & Eng, 2004; Olney et al., 1991; Parvataneni et al., 2007; Teixeira-Salmela et

al., 2001). As the stroke population displays varying and often asymmetrical gait patterns, specific location in the gait cycle where the peaks occur may be in a slightly different position to those shown in Figure 6.2. The largest joint power generation event is in the ankle plantarflexors just prior to toe off to propel the limb forward (A2) (Kepple et al., 1997; Winter, 1983). Two other main events are the hip flexors just prior to toe off to swing the lower limb through to the subsequent step (H3) and the hip extensors just after ground contact to thrust the hip forward (H1) (Liu et al., 2006; Neptune et al., 2004). Another power event, that provides little contribution to forward progression, occurs in the knee extensors following loading response in the transition to mid stance (K2) (Winter, 1983). Peak joint power generation was calculated as the highest recording in these four phases (see Figure 6.2). The reported power generation variables were taken as the median from successful trials.

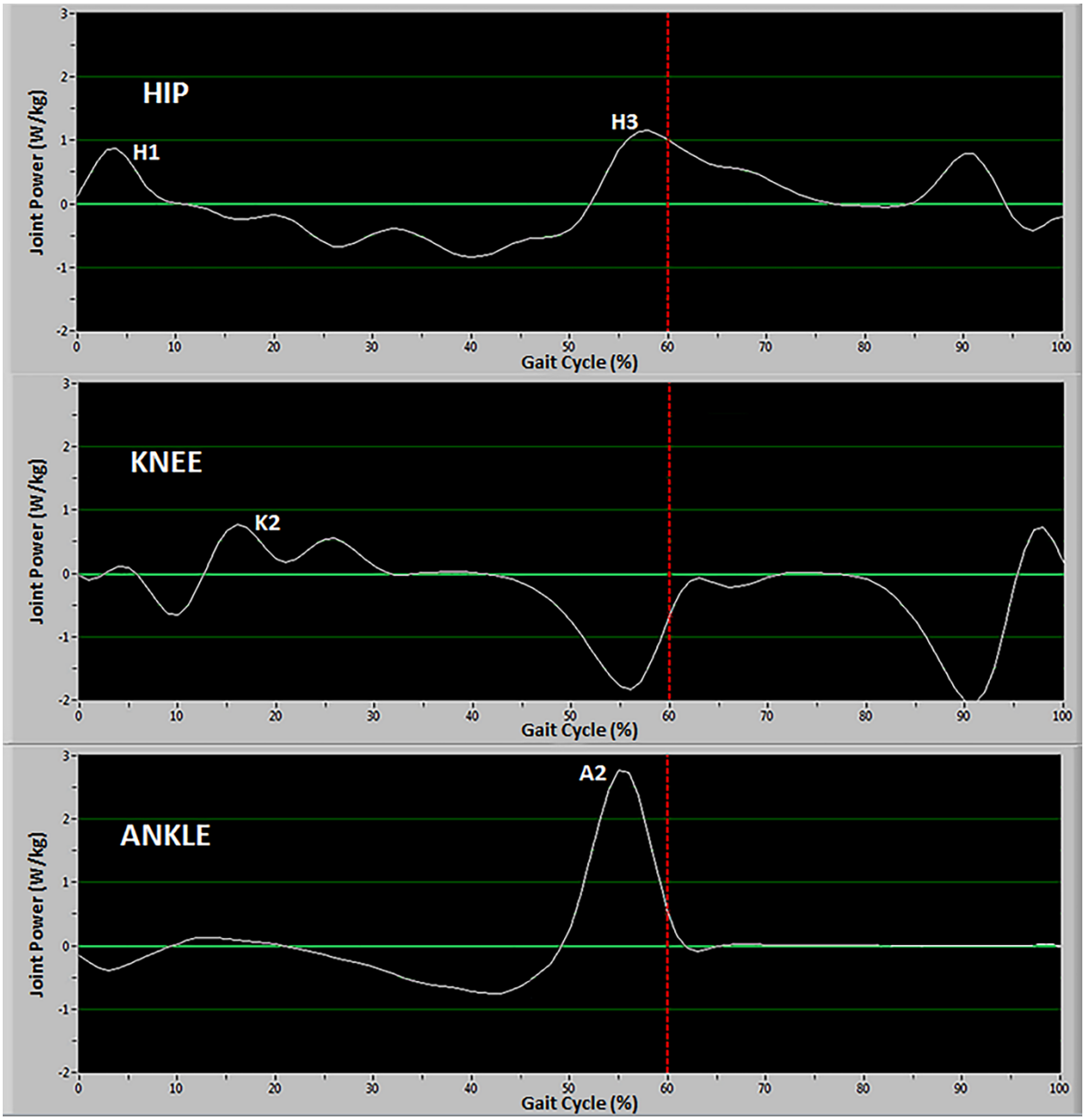

Figure 6.2. Joint power generation outcome measures in the sagittal plane. Example from an unimpaired and healthy participant, with data time normalised to 100% of the gait cycle. Positive indicates power generation whereas negative indicates power absorption. The vertical dashed line indicates toe off. The outcome measures to be used in the current study are the peaks occurring at A2, K2, H1 and H3. See the text for description of each measure.

6.3.4 Isometric muscle strength and power assessment

Following completion of the 3DGA, participants performed testing of isometric strength and RTD in an identical manner to Study Three. The HHD used in this study was the Lafayette Manual Muscle Testing System Model-01165 (Lafayette Instrument Company, Lafayette IN, USA). Similar to Study Three, additional foam padding (12mm thick EVA foam) was placed over the dynamometer to protect the participants from potential abrasions or pain (see Figure 5.1 from Study Three). To examine associations with the four peak power generation events during gait, the isometric strength and power of the ankle plantarflexors, hip flexors, hip extensors and knee extensors were assessed, in the same manner as Study Three. The order of assessment was the hip flexors first (seated position with hips and knees at 90°) followed by the knee extensors (seated position with hips and knees at 90°), the ankle plantarflexors (supine position with hips and knees extended with the ankle in neutral) and hip extensors (prone position with hips and knees extended). Each contraction was an MVC with participants asked to push or pull as hard and as fast as they could to enable the calculation of strength and RTD from the same trial. The non-paretic limb was assessed first, with a practice trial performed to ensure the participant understood the required contraction followed by two recorded trials. Two trials were then recorded for the paretic limb. The assessment of both limbs was completed by the same assessor (thesis author BFM; male with two years of experience with HHDs in healthy and neurological populations) who had demonstrated acceptable reliability in the administration of these tests in both healthy and stroke populations (Study Two and Three).

The data analysis of the HHD data was identical to previous studies in this thesis. The raw data from the HHD was filtered using a zero-phase shift 10Hz lowpass 4^{th} order Butterworth filter and then resampled to 1000Hz (the Lafayette device samples at 40Hz) using cubic

spline interpolation. The raw data was then normalised to lever arm (in metres) to calculate torque. The torque was then normalised to body mass (in kilograms). This process of normalisation of strength scores to lever arm and body mass has been used previously when examining the associations between strength and gait kinetics (Dallmeijer et al., 2011).

Isometric strength was calculated as the highest reading across the two trials. The RTD was assessed by examining successive 200ms intervals across the force trace to determine the peak RTD as described in Study Two and Three. The highest peak RTD recorded across the two trials was used for analysis. If the participant could not generate force against the HHD, a score of zero was recorded for that muscle group for strength and RTD.

6.3.5 Statistical analysis

The statistical analysis for this study was very similar to that of Study Three. The following section may contain some overlap with the information presented in Study Three, however to ensure a complete description of the relevant statistical methods used in this study, each step will be described in detail.

Descriptive statistics (means with standard deviations and medians with interquartile ranges for continuous variables and frequencies with percentages for categorical variables) were used to describe participant characteristics and outcome measures. The assumption of normality for some participant characteristics and outcome measures was not met and therefore, to provide a consistent analysis when examining differences between the Australian and Singaporean cohorts, Mann-Whitney U tests for continuous variables and Chi-Squared tests for categorical variables were performed. Spearman correlations were used to test associations between variables as they are robust to non-normally distributed data and commonly used as the nonparametric alternative for correlation coefficients (Bishara & Hittner, 2012).

Although not direct aims of the current study, bivariate correlations were performed to examine the association between the two recorded gait velocities (comfortable and fast gait velocity) as well as between strength and RTD measures of each muscle group (e.g. ankle plantarflexor strength with ankle plantarflexor RTD). The associations between gait velocity and joint power generation measures were also examined.

To provide a comprehensive analysis of the relationship between strength/RTD and joint power generation variables (first aim of the study), associations were examined without and with adjustment for pertinent confounders. Unadjusted associations were determined with Spearman correlations to examine the bivariate correlations between peak joint power generation and isometric strength/RTD. These bivariate correlations were performed for matching muscle groups between measures (e.g. ankle plantarflexor strength/RTD and APG at A2, hip flexor strength/RTD and hip flexor power generation at H3 etc.).

Multivariable linear regression was then performed to analyse the relationship between isometric strength/RTD and peak joint power generation during gait, adjusting for pertinent population confounders of age, gender, time since stroke and country of recruitment (with body mass already adjusted for within the strength/RTD and joint power generation scores). The assumption of normality was not met for the covariate of time since stroke and therefore, it was log transformed prior to all regression analyses. The first step was to create a base model containing the covariates of age, gender, time since stroke and country recruited. One outcome measure of either isometric strength or RTD was then entered into the model as the independent variable (e.g. ankle plantarflexor strength) with the corresponding peak joint power generation as the dependent variable (e.g. peak APG). This was repeated for each measure of muscle function and each corresponding measure of peak joint power generation. The change statistics were then examined to determine the incremental value of each

independent variable over the base model, with the change in R^2 (increment) and the *p*-value of the change reported. For example, to examine the relationship between ankle plantarflexor RTD and peak ankle joint power generation: dependent variable of peak ankle joint power generation, base model of covariates results in a hypothetical R^2 of 0.300, the total combined model (with ankle plantarflexor RTD included) results in a hypothetical R^2 of 0.555, which would correspond to a hypothetical R^2 increment of ankle plantarflexor RTD over the covariates of 0.255 and a significant *p*-value of 0.02 (arbitrary values used for the purposes of this example).

To examine the second aim of the study to compare between isometric strength and RTD in the relationship with peak joint power generation, a partial F-test was used (Harrell Jr., 2015). This was performed only if the preceding analysis failed to reveal which HHD measures (either strength or RTD) provided a stronger relationship with joint power generation. This method was performed by again creating a base model with covariates of age, gender, time since stroke and country recruited. The dependent variable was the measure of peak joint power generation for a particular muscle group (e.g. ankle joint power generation). A total model was then created with the base model and both measures of strength and RTD for a particular muscle group (e.g. adding both ankle plantarflexor strength and RTD to the base model). Strength was then removed from the total model to determine the effects that strength had on the total model. This was then repeated, by leaving strength in the model but removing RTD to examine the effects of RTD on the total model. Reported in the results is the total model R^2 (which includes the base model of covariates plus both strength and RTD), the reduction in R^2 (for each measure of strength and RTD when they are removed from the total model) and the *p*-value when each measure is removed (termed the *p*-value decrement). For example: there is a total model R^2 of 0.600 that contains the covariates plus ankle plantarflexor strength and RTD with peak APG as the dependent

variable, removing RTD from the total model results in the model R^2 dropping to 0.400 (reduction in R^2 of 0.200 and *p*-value decrement of 0.02) and removing strength from the total model results in the model R^2 dropping to 0.590 (reduction in R^2 of 0.010 and *p*-value decrement of 0.85) would indicate that RTD provides additional value in the relationship with peak APG over strength for the ankle plantarflexors (arbitrary values used for the example). If strength and RTD both return significant *p*-value decrements or both return non-significant *p*-value decrements, then no difference exists between measures.

The regression residuals for all models were assessed to determine if they adequately met the assumptions for least squares regressions. Significance was set at $p < 0.05$ for all analyses. Spearman correlation values were interpreted based on the suggestions provided by Evans (1996), with values taken as very strong (≥ 0.80), strong (0.60 to 0.79), moderate (0.40 to 0.59), weak (0.20 to 0.39) or very weak (< 0.20). All analyses were performed using the Statistical Package for Social Sciences version 23 (IBM Corp., Armonk, NY USA).

6.4 Results

6.4.1 Participant characteristics and outcome measures

To meet the *a priori* power calculation, 27 participants were recruited for the current study (age: 58 ± 15 years; gender: 52% male; time since stroke: 40 ± 58 months), with 13 from Australia and 14 from Singapore. Participant characteristics are provided in Table 6.1. Significant differences were observed between the Australian and Singaporean cohorts for race as well as both comfortable and fast paced gait velocity.

Table 6.1. Participant characteristics for Study Four

	Total (n = 27)	Australia (n = 13)	Singapore (n = 14)	Difference between groups
Gender, male *n* (%)	14 (52%)	5 (38%)	9 (64%)	$p = 0.18$
Age (years)	58 ± 15 (45/**58**/73)	59 ± 18 (41/**58**/75)	58 ± 13 (45/**56**/72)	$p = 0.72$
Height (cm)	164 ± 11 (157/**165**/171)	167 ± 10 (159/**167**/174)	161 ± 11 (150/**163**/169)	$p = 0.21$
Mass (kg)	68 ± 17 (57/**63**/79)	74 ± 20 (57/**73**/93)	62 ± 12 (55/**62**/68)	$p = 0.16$
Race				***p* < 0.01***
Caucasian, *n* (%)	12 (44.5%)	12 (92%)	0 (0%)	
Chinese, *n* (%)	12 (44.5%)	0 (0%)	12 (86%)	
Other, *n* (%)	3 (11%)	1 (8%)	2 (14%)	
Time since stroke (months)	40 ± 58 (4/**10**/63)	52 ± 72 (4/**20**/83)	28 ± 39 (4/**10**/38)	$p = 0.56$
Stroke paretic side, left *n* (%)	17 (63%)	8 (62%)	9 (64%)	$p = 0.88$
Type of stroke				$p = 0.59$
Haemorrhage, *n* (%)	9 (33%)	5 (38%)	4 (29%)	
Infarct, *n* (%)	18 (67%)	8 (62%)	10 (71%)	
Assistive devices worn outdoors#				$p = 0.35$
None, *n*	17	7	10	
Ankle foot orthosis, *n*	6	6	0	
Single point stick, *n*	6	3	3	
Wheelchair, *n*	1	0	1	
Gait velocity (m/s)				
Comfortable pace	0.89 ± 0.34 (0.53/**0.95**/1.16)	0.73 ± 0.27 (0.43/**0.80**/0.96)	1.04 ± 0.34 (0.85/**1.09**/1.28)	***p* < 0.01***
Fast pace^	1.15 ± 0.38 (0.91/**1.23**/1.35)	0.96 ± 0.36 (0.59/**0.99**/1.23)	1.40 ± 0.22 (1.25/**1.35**/1.51)	***p* < 0.01***

Note: continuous variables reported as mean ± standard deviation (25th/50th/75th percentiles). The 'difference between groups' column reports statistical differences between the Australian and Singaporean cohorts using the Mann-Whitney U test for continuous variables and the Chi-Squared test for categorical variables. * = significant difference between Australian and Singaporean cohorts; # = assistive devices listed were not used during testing, these are the usual assistive devices participants use to ambulate outdoors (some participants used multiple assistive devices, therefore percentages are not provided). Chi-Squared for 'assistive devices worn outdoors' used dichotomised data for either yes or no. ^ = fast pace 3DGA gait only measured in 23/27 participants (13/13 from Australia; 10/14 from Singapore).

Measures for peak joint power generation as well as the isometric strength and RTD for the paretic side are shown in Table 6.2 and the non-paretic side in Table 6.3. Outcome measures demonstrated significant differences between the cohorts for the paretic side peak ankle plantarflexor (A2) and hip extensor (H1) power generation for both comfortable and fast paced gait. Significant differences were also observed in the paretic side for isometric strength of the ankle plantarflexors. Differences between the cohorts were also observed for non-paretic side outcome measures (Table 6.3).

It should be noted that the total number of successful walking trials varied between participants (range: one to five successful trials per walking condition) due to issues in recorded data (human error resulting in the start of the gait trial being missed) and the difficulties in ensuring participants hit the force platform consistently. The assessor held potential safety concerns for the participant as they became more fatigued, in addition to potential detrimental effects on data validity. Close supervision was unable to be provided due to occlusion of the reflective markers used for the 3DGA. Therefore, the participant ceased performing additional trials when they indicated they did not wish to continue or the assessor identified any potential safety concerns (e.g. increasingly unsteady gait pattern). All participants had at least one successful walking trial at a comfortable pace. Also due to fatigue and safety concerns, not all participants were asked to walk at a fast pace across the laboratory. Consequently, only 23/27 participants have peak joint power generation measures for fast paced gait. A histogram is provided in Figure 6.3 to show the number of successful trials across participants for both comfortable and fast paced gait on the paretic and non-paretic sides. Similar to Study Three, for the isometric strength and RTD assessment, not all participants were able to lay prone due to discomfort or pain with positioning of the upper limb. Hip extensor strength and RTD were tested in 23/27 participants.

Table 6.2. Outcome measures for the paretic side

	Total (n = 27)	Australia (n = 13)	Singapore (n = 14)	Difference between groups
Comf peak power generation (W/kg)				
A2 (ankle plantarflexors)	1.42 ± 0.81 (0.67/**1.49**/1.99)	1.06 ± 0.72 (0.35/**1.16**/1.71)	1.75 ± 0.77 (1.05/**1.77**/2.58)	***p* = 0.04***
K2 (knee extensors)	0.69 ± 0.43 (0.40/**0.60**/0.79)	0.77 ± 0.57 (0.30/**0.60**/1.24)	0.62 ± 0.25 (0.43/**0.61**/0.74)	*p* = 0.92
H1 (hip extensors)	1.37 ± 1.32 (0.44/**0.94**/2.13)	0.61 ± 0.64 (0.14/**0.44**/0.77)	2.07 ± 1.41 (0.92/**1.98**/2.49)	***p* < 0.01***
H3 (hip flexors)	0.97 ± 0.66 (0.38/**0.87**/1.48)	0.70 ± 0.41 (0.31/**0.66**/1.05)	1.22 ± 0.76 (0.53/**1.30**/2.00)	*p* = 0.07
Fast peak power generation (W/kg)^				
A2 (ankle plantarflexors)	1.89 ± 0.98 (1.10/**2.18**/2.54)	1.42 ± 0.99 (0.47/**1.43**/2.28)	2.50 ± 0.56 (2.00/**2.50**/2.93)	***p* < 0.01***
K2 (knee extensors)	1.08 ± 0.63 (0.68/**0.84**/1.47)	1.20 ± 0.79 (0.52/**0.90**/1.60)	0.93 ± 0.31 (0.69/**0.79**/1.11)	*p* = 0.62
H1 (hip extensors)	2.07 ± 1.91 (0.50/**1.16**/3.40)	0.87 ± 0.81 (0.22/**0.92**/1.03)	3.63 ± 1.80 (2.26/**3.60**/4.62)	***p* < 0.01***
H3 (hip flexors)	1.44 ± 0.84 (0.82/**1.30**/2.03)	1.22 ± 0.98 (0.42/**0.87**/1.68)	1.72 ± 0.52 (1.06/**1.90**/2.15)	*p* = 0.05
Isometric strength (Nm/kg)				
Ankle plantarflexors	0.26 ± 0.11 (0.19/**0.24**/0.32)	0.20 ± 0.08 (0.14/**0.22**/0.26)	0.31 ± 0.12 (0.22/**0.30**/0.38)	***p* = 0.02***
Knee extensors	1.06 ± 0.32 (0.82/**1.03**/1.28)	0.95 ± 0.27 (0.75/**0.97**/1.20)	1.17 ± 0.34 (0.83/**1.13**/1.45)	*p* = 0.11
Hip extensors#	0.97 ± 0.46 (0.65/**0.92**/1.18)	1.06 ± 0.57 (0.63/**1.04**/1.36)	0.89 ± 0.37 (0.60/**0.88**/1.17)	*p* = 0.71
Hip flexors	0.63 ± 0.22 (0.44/**0.60**/0.78)	0.66 ± 0.21 (0.49/**0.67**/0.81)	0.60 ± 0.24 (0.41/**0.54**/0.77)	*p* = 0.36
Isometric RTD (Nm/s/kg)				
Ankle plantarflexors	0.43 ± 0.27 (0.27/**0.37**/0.56)	0.35 ± 0.17 (0.21/**0.35**/0.51)	0.51 ± 0.31 (0.29/**0.42**/0.68)	*p* = 0.16
Knee extensors	1.79 ± 0.98 (1.23/**1.53**/2.10)	1.54 ± 0.63 (1.20/**1.44**/2.06)	2.03 ± 1.19 (1.22/**1.58**/3.00)	*p* = 0.44
Hip extensors#	1.58 ± 0.94 (0.89/**1.49**/2.16)	1.62 ± 1.17 (0.80/**1.44**/2.19)	1.56 ± 0.77 (0.92/**1.49**/2.23)	*p* = 0.80
Hip flexors	1.20 ± 0.58 (0.69/**1.12**/1.70)	1.33 ± 0.54 (0.96/**1.12**/1.76)	1.08 ± 0.60 (0.64/**0.78**/1.56)	*p* = 0.13

Note: values reported are mean ± standard deviation (25th/**50th**/75th percentiles). The 'difference between groups' column reports statistical differences between the Australian and Singaporean cohorts using the Mann-Whitney U test. Comf = comfortable; ^ = fast pace 3DGA gait only measured in 23/27 participants (13/13 from Australia; 10/14 from Singapore); # = hip extensors only measured in 23/27 participants (10/13 from Australia; 13/14 from Singapore); ***** = significant difference between Australian and Singaporean cohorts.

Table 6.3. Outcome measures for the non-paretic side

	Total (n = 27)	Australia (n = 13)	Singapore (n = 14)	Difference between groups
Comf peak power generation (W/kg)+				
A2 (ankle plantarflexors)	2.51 ± 0.84 (1.86/**2.47**/3.00)	2.17 ± 0.75 (1.77/**2.02**/2.50)	2.87 ± 0.81 (2.48/**2.68**/3.13)	***p* = 0.02***
K2 (knee extensors)	0.69 ± 0.52 (0.35/**0.59**/0.79)	0.82 ± 0.67 (0.30/**0.69**/1.02)	0.54 ± 0.24 (0.39/**0.48**/0.73)	*p* = 0.36
H1 (hip extensors)	1.55 ± 1.15 (0.74/**1.25**/2.09)	0.85 ± 0.48 (0.42/**0.84**/1.16)	2.30 ± 1.20 (1.30/**2.04**/3.55)	***p* < 0.01***
H3 (hip flexors)	1.32 ± 0.73 (0.75/**1.36**/1.75)	0.95 ± 0.44 (0.60/**0.78**/1.36)	1.72 ± 0.78 (1.27/**1.73**/2.03)	***p* < 0.01***
Fast peak power generation (W/kg)^				
A2 (ankle plantarflexors)	3.69 ± 1.87 (2.67/**2.98**/4.36)	3.88 ± 2.43 (2.36/**2.73**/4.79)	3.44 ± 0.75 (2.89/**3.17**/3.89)	*p* = 0.32
K2 (knee extensors)	1.21 ± 0.78 (0.74/**0.82**/1.66)	1.38 ± 0.93 (0.76/**0.93**/2.18)	0.98 ± 0.49 (0.71/**0.75**/1.19)	*p* = 0.19
H1 (hip extensors)	2.00 ± 1.30 (0.81/**1.73**/2.50)	1.18 ± 0.71 (0.59/**0.85**/1.71)	3.07 ± 1.12 (2.09/**2.99**/4.22)	***p* < 0.01***
H3 (hip flexors)	1.87 ± 0.90 (1.19/**1.59**/2.32)	1.65 ± 0.82 (1.06/**1.50**/2.23)	2.16 ± 0.95 (1.36/**2.28**/2.54)	*p* = 0.15
Isometric strength (Nm/kg)				
Ankle plantarflexors	0.38 ± 0.12 (0.32/**0.36**/0.46)	0.38 ± 0.14 (0.28/**0.35**/0.46)	0.38 ± 0.10 (0.32/**0.36**/0.45)	*p* = 0.85
Knee extensors	1.18 ± 0.31 (1.00/**1.18**/1.41)	1.09 ± 0.30 (0.85/**1.02**/1.30)	1.27 ± 0.30 (1.07/**1.30**/1.46)	*p* = 0.10
Hip extensors#	1.31 ± 0.50 (0.96/**1.15**/1.78)	1.54 ± 0.55 (0.97/**1.55**/2.07)	1.13 ± 0.39 (0.77/**1.10**/1.40)	*p* = 0.11
Hip flexors	0.81 ± 0.27 (0.58/**0.79**/0.99)	0.91 ± 0.27 (0.73/**0.88**/1.13)	0.71 ± 0.24 (0.50/**0.64**/0.83)	***p* = 0.03***
Isometric RTD (Nm/s/kg)				
Ankle plantarflexors	0.67 ± 0.31 (0.46/**0.53**/0.84)	0.72 ± 0.30 (0.48/**0.61**/1.00)	0.63 ± 0.31 (0.42/**0.52**/0.70)	*p* = 0.41
Knee extensors	2.04 ± 0.98 (1.20/**1.99**/2.62)	1.85 ± 0.76 (1.14/**1.76**/2.46)	2.21 ± 1.15 (1.17/**2.05**/3.02)	*p* = 0.53
Hip extensors#	2.53 ± 1.26 (1.61/**2.19**/3.53)	3.02 ± 1.49 (1.73/**2.55**/4.35)	2.16 ± 0.95 (1.34/**1.96**/2.76)	*p* = 0.17
Hip flexors	1.65 ± 0.77 (1.06/**1.48**/2.00)	1.96 ± 0.76 (1.28/**1.80**/2.64)	1.37 ± 0.68 (0.82/**1.18**/1.79)	***p* = 0.03***

Note: values reported are mean ± standard deviation (25th/**50th**/75th percentiles). The 'difference between groups' column reports statistical differences between the Australian and Singaporean cohorts using the Mann-Whitney U test. Comf = comfortable; + = non-paretic side gait measures for comfortable pace was measured in 25/27 participants (13/13 from Australia; 12/14 from Singapore); ^ = non-paretic side fast pace 3DGA gait only measured in 23/27 participants (13/13 from Australia; 10/14 from Singapore); # = hip extensors only measured in 23/27 participants (10/13 from Australia; 13/14 from Singapore); ***** = significant difference between Australian and Singaporean cohorts.

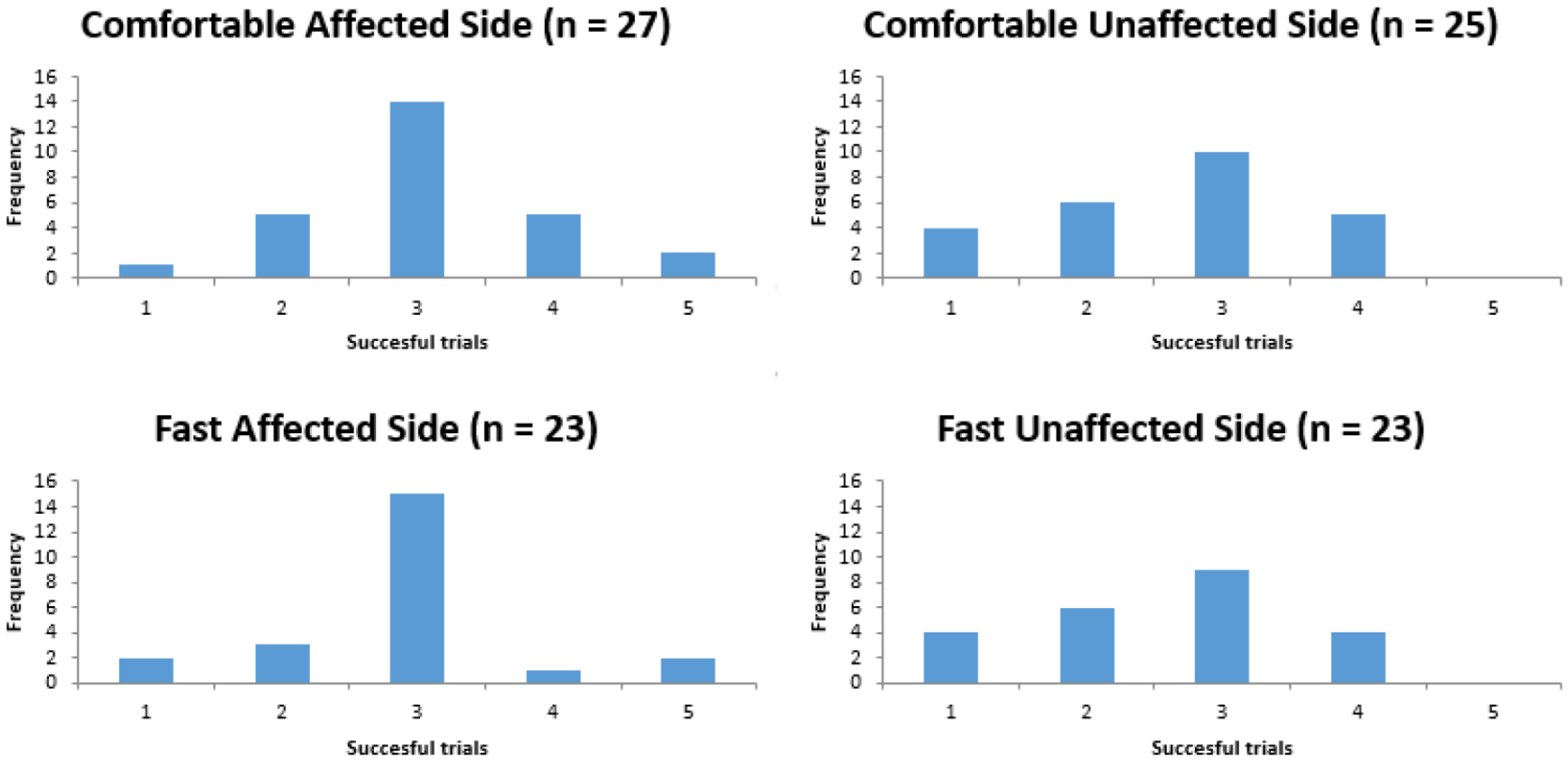

Figure 6.3. Histogram plots showing the number of successful trials across participants for comfortable and fast paced power generation for the paretic (affected) and non-paretic (unaffected) sides.

Secondary analyses of the data examined the association between comfortable gait velocity and peak joint power generation measures of the paretic side during comfortable gait and revealed very strong correlations for A2 (rho = 0.84), H1 (rho = 0.81) and H3 (rho = 0.86) whilst a moderate correlation was shown for K2 (rho = 0.46). Fast paced measures revealed a similar trend (albeit with a smaller correlation for APG at A2) with strong to very strong correlations for A2 (rho = 0.66), H1 (rho = 0.81) and H3 (rho = 0.88) with a weak correlation for K2 (rho = 0.30). This smaller correlation value for APG in fast paced compared with comfortable paced gait suggests a reliance on proximal muscle groups when walking at fast speeds, as has been observed previously in neurological populations (Williams, Morris, Schache, & McCrory, 2010; Williams & Schache, 2016). This result occurs even when, similar to Study Three, there is a very strong correlation between comfortable and fast gait velocity (rho = 0.89). There were also very strong correlations between measures of isometric strength and RTD of the paretic side across the lower limb muscle groups, similar to Study Three (rho = 0.82 to 0.91).

6.4.2 Bivariate correlations

The bivariate associations of isometric strength and RTD with peak joint power generation are provided in Table 6.4 for the paretic side. There was a significant, strong association between isometric ankle plantarflexor strength and peak APG (A2) during comfortable and fast paced gait (rho = 0.65 and 0.75 for comfortable and fast gait respectively). Isometric ankle plantarflexor RTD showed significant moderate associations with peak APG (A2) (rho = 0.59 and 0.54 for comfortable and fast gait respectively). Hip flexor strength also showed significant moderate correlations with peak hip flexor power generation (H3) (rho = 0.42 and 0.44 for comfortable and fast gait respectively), whilst hip flexor RTD showed non-significant weak associations (rho = 0.36 and 0.27 respectively). Knee extensor strength and

RTD showed very weak to moderate correlation values with knee extensor power generation at K2 (rho = 0.06 to 0.42) and hip extensor strength and RTD showed weak correlations with hip extensor power generation at H1 (rho = 0.28 to 0.39).

Table 6.4. Bivariate associations between the paretic side peak joint power generation measures and isometric strength and rate of torque development

Muscle function variables	Peak joint power generation variables	Comfortable gait	Fast gait
Isometric Strength			
Ankle plantarflexors	A2	**0.65^**	**0.75^**
Knee extensors	K2	**0.42**	0.07
Hip extensors	H1	0.29	0.28
Hip flexors	H3	**0.42**	**0.44**
Isometric RTD			
Ankle plantarflexors	A2	**0.59**	**0.54**
Knee extensors	K2	0.37	0.06
Hip extensors	H1	0.38	0.39
Hip flexors	H3	0.36	0.27

Note: all values are Spearman correlations, significant correlations in bold. ^ = strong correlation according to the thresholds of Evans (1996); A2 = peak ankle power generation just prior to toe off; K2 = peak knee power generation during stance; H1 = peak hip power generation during early to mid-stance; H3 = peak hip power generation just prior to toe off; RTD = rate of torque development.

Correlations between the non-paretic side variables are shown in Table 6.5. No significant correlations were observed, with values ranging from very weak to weak (absolute rho = 0.01 to 0.39).

Table 6.5. Bivariate associations between the non-paretic side peak joint power generation measures and isometric strength and rate of torque development

Muscle function variables	Peak joint power generation variables	Comfortable gait	Fast gait
Isometric Strength			
Ankle plantarflexors	A2	0.00	0.21
Knee extensors	K2	0.18	0.18
Hip extensors	H1	0.06	0.02
Hip flexors	H3	-0.11	0.07
Isometric RTD			
Ankle plantarflexors	A2	0.10	0.29
Knee extensors	K2	0.39	0.24
Hip extensors	H1	0.01	-0.02
Hip flexors	H3	-0.12	0.02

Note: all values are Spearman correlations with no correlations returning significant values. A2 = peak ankle power generation just prior to toe off; K2 = peak knee power generation during stance; H1 = peak hip power generation during early to mid-stance; H3 = peak hip power generation just prior to toe off; RTD = rate of torque development.

6.4.3 Multivariate relationships

The results from the multivariate regression analyses are shown in Table 6.6. The base model column shows the relationship between the covariates (age, gender, time since stroke and country recruited) and each dependent variable measure of joint power generation of the paretic side. Interesting to note is the large value seen for the base model in the relationship with peak ankle plantarflexor (R^2 = 0.408 and 0.469 for comfortable and fast paced power generation respectively) as well as hip extensor power generation (R^2 = 0.562 and 0.607 for comfortable and fast paced power generation respectively). This indicates that these outcome measures are potentially indicative of the covariates used in this study. The focus however was on the incremental ability of isometric strength and RTD over the base model R^2.

Knee and hip strength or RTD did not demonstrate a significant incremental increase in describing the relationship with peak knee or hip joint power generation over a base model containing the covariates of age, gender, time since stroke and country recruited. In contrast, a significant increment was shown for the relationship between ankle plantarflexor strength and peak APG at a comfortable and fast pace over and above the base model. Ankle plantarflexor RTD also provided a significant increase in the R^2 over a base model for comfortable paced APG, but not for fast paced APG.

Table 6.6. Regression results for the relationship between isometric strength and rate of torque development with peak joint power generation during gait of the paretic side

Independent variable	Dependent variable	Comfortable gait power				Fast gait power			
		Base model R^2	R^2 increment	*p*-value of increment	Total R^2	Base model R^2	R^2 increment	*p*-value of increment	Total R^2
Strength (Nm/kg)									
Ankle plantarflexors	A2	0.408	0.206	**< 0.01***	0.614	0.469	0.167	**0.01***	0.636
Knee extensors	K2	0.091	0.097	0.13	0.189	0.080	0.025	0.50	0.105
Hip extensors	H1	0.562	0.007	0.61	0.569	0.607	0.007	0.62	0.615
Hip flexors	H3	0.442	0.058	0.13	0.500	0.106	0.172	0.06	0.278
RTD (Nm/s/kg)									
Ankle plantarflexors	A2	0.408	0.117	**0.03***	0.525	0.469	0.064	0.14	0.533
Knee extensors	K2	0.091	0.068	0.21	0.159	0.080	0.007	0.73	0.087
Hip extensors	H1	0.562	0.027	0.31	0.589	0.607	0.038	0.24	0.646
Hip flexors	H3	0.442	0.040	0.22	0.481	0.106	0.049	0.34	0.155

Note: results from linear regression models, with analyses adjusted for age, gender, time since stroke and country recruited (body mass adjusted for within strength/RTD and joint power generation scores). R^2 increment is the change in R^2 of each variable over a base model (age, gender, time since stroke and country recruited). The *p*-value change is the significance level of the R^2 increment. Total R^2 is the total combined model with covariates (Base model R^2) and the independent variable (R^2 increment). Bold *p*-values with * indicate significance. RTD = rate of torque development. A2 = peak ankle power generation just prior to toe off; K2 = peak knee power generation during stance; H1 = peak hip power generation during early to mid-stance; H3 = peak hip power generation just prior to toe off; RTD = rate of torque development.

6.4.4 Partial F-test for comparison of strength and RTD

The last step in analysis was to determine if strength or RTD provided a stronger association with joint power generation during gait on the paretic side. As neither strength nor RTD for the knee and hip provided any significant incremental association with knee and hip power generation over the base model, only the ankle joint was examined further. For fast paced peak APG, it can be observed in Table 6.6 that ankle strength has a stronger association with APG compared with ankle RTD due to the significant incremental value for ankle strength over the base model and the non-significant incremental value of ankle RTD. However, as both ankle strength and RTD provided a significant incremental improvement over the base model in the association with comfortable peak APG, a partial F-test was performed to determine if ankle strength provided significant incremental value over ankle RTD when describing the relationship with comfortable APG of the paretic side (Table 6.7). The results from the partial F-test revealed that ankle plantarflexor strength provides significant additional value over ankle plantarflexor RTD, due to the significant *p*-value when strength was removed from the total model and the non-significant *p*-value when RTD was removed from the total model. The analyses combined indicate that isometric ankle plantarflexor strength has a stronger relationship with comfortable and fast paced peak APG compared with isometric ankle plantarflexor RTD.

Table 6.7. Comparison between isometric plantarflexor strength and rate of torque development for the relationship with peak ankle power generation of the paretic side

	Comfortable peak power generation		
	Total R^2	**Reduction in R^2**	***p*-value of decrement#**
Ankle plantarflexors	0.636		
Remove Strength		0.111	**0.02***
Remove RTD		0.022	0.29

Note: Total R^2 column reflects the total model containing the covariates (age, gender, time since stroke and country recruited) and measures of ankle plantarflexor strength and RTD. # = *p*-value of decrement is from a partial F-test evaluating the additional value of strength over RTD, adjusting for covariates, and vice versa. Bold *p*-value with * indicates significance with one measure providing significant incremental value over the other measure; RTD = rate of torque development.

6.5 Discussion

This study aimed to assess the relationships between HHD measures of strength and RTD with joint power generation during gait following stroke. The results from the current study indicate that ankle plantarflexor strength and RTD had a significant, strong association with peak APG during gait following stroke. In contrast, both knee and hip strength and RTD provided very weak to moderate correlations with peak knee and hip power generation during gait and thus HHD measures of knee or hip muscle function should not be used to infer knee or hip power generation. A comparison between isometric strength and RTD demonstrated that ankle plantarflexor strength had a stronger relationship with APG compared with RTD.

The results of the current study demonstrated a slightly stronger association between ankle plantarflexor strength (as measured by HHD) and peak APG than previous studies in other neurological populations (Dallmeijer et al., 2011; Kahn & Williams, 2015). This may be due to multiple factors such as the assessment methods of isometric strength, the reliability of the assessor, the sample size and the population tested. The two previous studies as well as the current study all tested isometric ankle plantarflexor strength with the Lafayette brand of HHD with the participants in a supine position and the ankle joint in neutral. However, the study by Dallmeijer et al. (2011) used a different supine testing position for ankle plantarflexor strength with the hips and knees flexed at 90° and the lower limb resting on a small stool, whereas the current study and the study by Kahn and Williams (2015) had the hips and knees fully extended on a plinth. The assessment protocol with the hips and knees at 90° used by Dallmeijer et al. (2011) does not reflect the position of the lower limb during gait and as such may explain why the current study found a different correlation value. Another discrepancy between the studies is that the strength values for the current study and

the study by Dallmeijer et al. (2011) were reported as torque normalised to body mass (Nm/kg), whilst the study by Kahn and Williams (2015) did not normalise the torque values to body mass (Nm). Strength scores need to be normalised to body mass to allow comparison between participants (e.g. there is a large difference in relative strength between a 50kg person producing 30Nm of torque and a 100kg person producing 30Nm of torque). Joint power generation is normalised to body mass and to allow an unbiased comparison between power generation and isometric strength, strength values need to also be normalised to body mass. This could also explain why the correlation values reported in the current study are higher than the previous studies.

Reliability of the strength assessor is also important, especially when using HHD. The previous studies by Dallmeijer et al. (2011) and Kahn and Williams (2015) did not test the reliability of the strength assessor used in their studies, which may explain the lower correlation values between isometric plantarflexor strength and APG. The strength assessor in the current study (thesis author BFM) had a comprehensive analysis of their reliability and validity in Studies Two and Three of this thesis. The most apparent difference between the three studies is the neurological population tested, with the current study of the stroke population, the Dallmeijer et al. (2011) study of bilateral spastic cerebral palsy and the study by Kahn and Williams (2015) of people following a traumatic brain injury. As there are potential differences in the strength deficits and gait patterns between the populations, comparison between the three studies should be done with caution. Nonetheless, when examining the associations between strength and power generation during gait, it is important to ensure the strength assessment positions reflect those seen during gait, the strength and joint power generation values are normalised to body mass and the strength assessor shows acceptable reliability for assessment of strength in the population being tested.

Ankle plantarflexor strength demonstrated a strong relationship with APG in this study, despite strength being assessed during a static, isometric condition and power generation in a dynamic gait condition. The ankle plantarflexors act as a spring or catapult during gait (Sawicki, Lewis, & Ferris, 2009). The Achilles tendon stores elastic energy during the majority of the stance phase and then produces a timed rapid recoil at push-off to contribute the majority of APG recorded during gait (Ishikawa, Komi, Grey, Lepola, & Bruggemann, 2005; Sawicki et al., 2009). This stretch and recoil of the Achilles tendon therefore allows the muscle fibres to remain almost isometric in nature, with the majority of APG during gait provided by this Achilles tendon recoil (Sawicki et al., 2009). Muscle groups spend much less metabolic energy to produce force during an isometric contraction (Ryschon, Fowler, Wysong, Anthony, & Balaban, 1997) and therefore, the elastic recoil may enhance movement efficiency by reducing the metabolic energy during gait (Sawicki et al., 2009). Assessment of isometric strength is still warranted as stronger isometric force could potentially optimise this elastic recoil. Other assessments that replicate or mimic the Achilles tendon recoil, such as sled jumps measured with a string potentiometer (Williams, Clark, Hansson, & Paterson, 2014a), may provide a stronger association with gait function after stroke and warrant investigation. Nevertheless, the strong relationship between isometric ankle plantarflexor strength and APG indicates that assessment of isometric strength is still warranted.

Another interesting finding of the current study was that knee and hip strength and RTD provided very weak to moderate correlations with peak knee and hip power generation during gait. Isometric hip flexor strength showed significant moderate correlations with hip flexor power generation in the current study but failed to provide significant incremental value in the regression models. This is particularly interesting given the very strong correlation values between hip power generation and gait velocity and the strong relationship

between isometric hip flexor strength and gait velocity shown in Study Three. This indicates that although both isometric hip flexor strength and hip power generation during gait had a strong relationship with gait velocity, the isometric strength assessment did not reflect hip power generation during gait. As discussed in the previous paragraph, clinically accessible assessments that better reflect the dynamic nature of gait may be needed to provide a stronger relationship with hip power generation during gait. The HHD measures of the knee and hip used in the current study demonstrated weak to moderate correlations with knee and hip power generation during gait. Although, as hip flexor strength showed a strong relationship with gait velocity in Study Three, assessment of isometric hip flexor strength is still warranted.

The current study found that ankle plantarflexor strength had a stronger association with peak APG compared with ankle plantarflexor RTD. The RTD has been rarely assessed in the stroke population and the use of clinically accessible equipment to measure RTD was a novel aspect of the current study. The finding that isometric strength provides additional value over RTD in the relationship with APG is similar to Study Three that showed the same results for gait velocity. There was a strong correlation between the measures of isometric strength and RTD across the lower limb muscle groups (rho = 0.82 to 0.91). This indicates that RTD does not fully explain the variance in isometric strength, with still a substantial amount of unexplained variance (17 to 33%). The result that ankle plantarflexor strength had a stronger association with peak APG over ankle plantarflexor RTD is interesting as both power generation and RTD are time dependent. It would be logical to hypothesise that RTD would show a larger correlation value with power generation than strength because they both require quick muscle contractions. Previous studies in neurological populations have suggested that research examining the relationships between muscle function and gait should focus on clinically feasible power based measures of muscle function (Dorsch et al.,

2012; Kahn & Williams, 2015). Previous research has shown that RTD can provide stronger associations with measures of physical function in various clinical populations including stroke (Moreau et al., 2012; Pohl et al., 2002; Winters & Rudolph, 2014), which provided the rationale for the current study. The disparity between the current study and previous studies may be due to the previous studies using expensive, laboratory-based dynamometers to assess RTD. However, such dynamometers are rarely used in clinical settings due to their expensive and cumbersome nature. Therefore, a major strength of the current study is the use of a HHD, as these instruments are clinically accessible and can be used for routine assessment of patient cohorts. Future research may wish to develop other methods of assessing RTD for use in a clinical setting or examine dynamic measures of muscle power. Dynamic measures of either muscle strength or power may have a stronger association with joint power generation following stroke.

6.5.1 Limitations

It would be erroneous to imply that correlations indicate causation. Improvements in plantarflexor isometric strength or RTD may not result in improved peak APG during gait following stroke, and conversely improvements in hip flexor strength or RTD could result in improvements in peak hip flexor power generation despite the relatively low correlation between these variables. The aim of this study was to determine the relationship between isometric strength and RTD and joint power generation during gait. Further investigation is required to determine the effects of improved strength or RTD on joint power generation following stroke.

As discussed in Study Three, the use of HHD, which tests isometric strength and RTD, may not accurately represent the dynamic muscle actions seen during gait. The participant positions and joint angles used during the HHD assessment do not reflect the joint angles

that are seen during walking to produce joint power generation (e.g. hip flexor strength assessment). As discussed, the Achilles tendon acts as a spring or catapult during gait, with the rapid recoil of the Achilles tendon at push off producing the majority of the peak APG (Sawicki et al., 2009). Other assessments that replicate or mimic this Achilles tendon recoil could potentially provide a stronger association with gait function after stroke. Despite the concerns of participant positions during HHD assessment, HHD is currently one of the most clinically feasible devices for the assessment of muscle strength (Stark et al., 2011). Future research may wish to examine other dynamic measures of muscle strength or power and how such measurement protocols relate to joint power generation.

This study used two different laboratories, which may limit the results of this study. Ideally inter-laboratory reliability would be established prior to data collection, however this was problematic due to the international study design. To reduce potential errors, all marker placement was performed by the same assessor (thesis author BFM) and all data was processed using the same methods. To account for potential differences between laboratories, all regression analyses were adjusted for the laboratory used (Australia or Singapore). Another potential limitation is the range of successful walking trials between participants, with participants completing between one and five successful trials. This potentially affects the joint power generation results by increasing the potential for erroneous results. Ideally five successful trials would have been collected for every participant, however issues arose in ensuring the participant consistently hit the force platform (due to the often asymmetrical gait pattern of those following stroke) and there were some issues with recorded data due to human error of missing the start of the gait trial. To ensure duty of care to the participants, continuation of the walking trials to obtain five successful trials was not done in those showing signs of fatigue or deteriorating gait patterns, which resulted in a range of successful trials between participants (refer to Figure 6.3 in Section 6.4.1).

Significant differences were observed between the Australian and Singaporean cohorts in their self-selected comfortable and fast paced gait velocity during gait assessment. Despite not including a measure of stroke severity in this study, gait velocity is commonly used as an overall indicator of function (Salbach et al., 2001; van de Port et al., 2008); therefore the differences in gait velocity between countries potentially indicates differences in the functional level between the Australian and Singaporean cohorts. This difference in gait velocity between the cohorts may also explain why significant differences in power generation variables were seen for A2 and H1 power generation events at both comfortable and fast paced gait. The associations in this study demonstrated that those with higher peak APG (A2) also had higher isometric ankle plantarflexor strength. There was also a significant difference between the cohorts for isometric ankle plantarflexor strength. Despite these differences, the analyses for this study included both cohorts combined which provided a greater heterogeneity of data that helped identify a relationship compared to the more clustered data from each site, and as such further examination of how the relationship changed across countries was not performed.

Whilst this study has shown HHD assessment of isometric ankle plantarflexor strength to have a strong relationship with peak APG during gait, there are still other potential influencing factors that need to be considered. For example, this study did not measure lower limb spasticity, which may affect ankle muscle function. This study also only examined one outcome measure of joint power generation, namely the peak power generated in specific phases of the gait cycle. Other research has examined work throughout the gait cycle (the area under the power curve) (Williams & Schache, 2016). Whilst such alternate measures may provide informative data on the joint kinetics during gait, previous research examining relationships between HHDs and joint power generation in other neurological populations have used the peak power generated during the gait cycle (Dallmeijer et al., 2011; Kahn &

Williams, 2015). Future research may wish to examine other measures of joint power generation, such as work throughout the gait cycle, to further examine the relationship between HHD measures of strength and RTD and joint kinetics during gait following stroke.

6.6 Conclusion

In summary, measurements of ankle plantarflexor isometric strength and RTD displayed significant moderate to strong associations with peak APG. In contrast, HHD measures of knee and hip isometric strength and RTD revealed very weak to moderate associations with knee and hip peak power generation during gait in the stroke population. When comparing isometric strength and RTD, ankle plantarflexor isometric strength provided significant incremental value over ankle RTD in the relationship with APG. Therefore, further research should consider assessment of isometric ankle strength that can be measured quickly and easily in a clinical setting for routine assessment.

The implication of the current study follows on from Study Three in that isometric ankle plantarflexor strength measured with HHD shows a strong relationship with both gait velocity (Study Three) and APG during gait in the stroke population (Study Four). Ankle plantarflexor strength may provide clinicians with information on the gait of the stroke population, with this program of research suggesting further research is needed to develop and assess the effect of interventions that target ankle plantarflexor strength in the hope of also improving gait after stroke.

CHAPTER SEVEN: DISCUSSIONS, RECOMMENDATIONS AND CONCLUSIONS

This program of research explored the use of HHD for assessment of isometric strength and power and the relationships of strength and power with gait function following stroke. This is the first time that HHD has been used for the assessment of isometric power. This thesis aimed to: 1) systematically review the previous literature that had provided correlations between isometric strength and gait velocity following stroke; 2) to provide the psychometric properties of a clinically feasible device (HHD) for the assessment of isometric strength and power in a healthy and stroke population; 3) to determine which variable (isometric strength or power) had a stronger relationship with gait velocity and joint power generation during gait following stroke; and 4) to examine which HHD derived variables from each of the lower limb muscle groups had the strongest relationship with gait velocity and joint power generation after stroke.

7.1 Synthesis of major findings

The systematic review in Study One (Chapter 3) was undertaken as it became apparent whilst performing the narrative literature review (Chapter 2) that there was a large amount of previous research, with differing methodologies and results, that had examined the associations between lower limb isometric strength and gait velocity after stroke. The systematic review identified 21 articles with equivocal correlation values reported between isometric strength and gait velocity. There were many methodological variations between the studies in relation to the sample size, the muscle groups assessed and the device used for strength testing. The majority of studies only examined the isometric strength of the knee extensors. Of those included studies with a relatively large sample size and good

methodological quality, the ankle dorsiflexors appeared to have the strongest association with gait velocity. Caution is needed when examining the results of Study One as the majority of studies had a small sample size and poor methodological quality. The systematic review in Study One (Chapter 3) as well as the narrative review (Chapter 2) provided the rationale for the subsequent studies by demonstrating a lack of previous high quality research that has examined the associations between isometric muscle function and gait following stroke.

Prior to addressing the lack of high quality research, Study Two (Chapter 4) was undertaken to examine the reliability and validity of a clinically feasible method using HHD for the assessment of isometric strength, as well as RFD. Prior to this thesis, HHD had never been used for the assessment of RFD. The results of Study Two informed the design of the subsequent studies in the stroke cohorts. Previous studies had used many different algorithms for the calculation of RFD, therefore Study Two examined the reliability of a variety of methods to calculate RFD. Two versions of HHD were included in the study and properties of intra-rater and inter-rater reliability were examined as well as concurrent validity compared with a fixed laboratory-based dynamometer. The results demonstrated good to excellent intra-rater and inter-rater reliability for measures of isometric strength and RFD for both versions of HHD. Good to excellent concurrent validity was found for strength and RFD for the majority of muscle groups, although mostly poor to moderate validity was shown for the ankle muscle groups. This lower than expected validity for measures of ankle strength and power needs to be considered, although the ankle attachment for the fixed laboratory-based dynamometer resulted in inaccurate recordings (with higher SEM and MDC results) as the attachment head did not securely fit within the load cell of the dynamometer. Similar problems have been reported previously for the particular laboratory-based dynamometer used in Study Two (Kaminski et al., 1995). Nevertheless, the HHD was

still used in subsequent studies due to the good to excellent intra-rater and inter-rater reliability as well as the good to excellent concurrent validity for the majority of lower limb muscle groups.

Study Three (Chapter 5) was undertaken to examine the relationship between HHD measures of isometric strength and power and gait velocity following stroke. Study Three extended on the previous research identified in Study One to include a relatively large sample size. Study Three also extended on the results of Study Two, to examine both strength and RTD using HHD. The results of Study Three demonstrated HHD measures of isometric strength and RTD had good to excellent test-retest reliability for all muscle groups on both the paretic and non-paretic limb in the stroke cohort (ICC $\geq$ 0.82). Interestingly, isometric strength demonstrated a stronger association with gait velocity following stroke. Isometric RTD still provided a significant relationship with gait velocity and despite the other findings of Study Three, measures of muscle power may still be important for gait after stroke. Other measures of dynamic muscle power that reflect the spring actions of muscles seen during gait may provide different associations compared with muscle strength.

Comparison of the strength of seven lower limb muscle groups demonstrated the strength of the ankle plantarflexors and hip flexors explained the largest amount of variance in gait velocity following stroke. This seems logical as the ankle plantarflexors and hip flexors provide the majority of power generation during gait to propel the limb forward at the push off phase of gait (Kepple et al., 1997; Liu et al., 2006; Neptune et al., 2004). The regression models created in Study Three, with either ankle plantarflexor or hip flexor strength included, explained 49-50% of the variance in gait velocity. These results support the assessment of isometric strength with HHD in stroke rehabilitation and future research could

examine those important muscle groups for gait, namely the ankle plantarflexors and hip flexors.

Study Four (Chapter 6) was undertaken to determine whether measures of strength and RTD from a HHD had a strong relationship with joint power generation during gait in the stroke population. Study Four extended on the results of Study Three to examine joint power generation, an important variable in gait function that is crucial to progress the body forward. Knee and hip measures of strength and power had weak to moderate correlations with knee and hip power generation during gait. In contrast, isometric measures of ankle plantarflexor strength and RTD showed significant moderate to strong correlations with APG. Similar to Study Three, the comparison between strength and power of the plantarflexors demonstrated that isometric strength explained more of the variance in ankle joint power generation following stroke compared with isometric power.

Overall, the results from this program of research: 1) identified the need for further high quality research that examined the associations between strength and gait velocity following stroke; 2) provided a psychometrically-sound and clinically accessible device for assessment of strength and power; 3) examined the associations between strength and gait velocity on a large scale compared to previous research; 4) assessed isometric muscle power in a stroke cohort; and 5) examined the associations between strength and power with joint power generation following stroke.

7.2 Clinical significance

This thesis has the potential to inform clinical practice when considering gait function following stroke. This thesis examined the ability of a commonly used and clinically accessible device (HHDs) to assess isometric muscle strength and power. The results of this

thesis provide an indication that HHD can be reliably used in the stroke population for assessment of isometric strength and power, which could aid clinicians in their understanding of muscle function during the rehabilitation of their patients. The HHD used in this program of research is an accessible and psychometrically-sound device that enhances the objective assessment of isometric strength in a clinical setting. Although the HHDs provide an instantaneous measure of peak force, the calculation of RFD or RTD requires additional post-processing of the data, which may limit the clinical applicability of using HHD to clinically assess these outcomes. To overcome this issue where clinicians may not have the necessary technical skills to calculate RFD or RTD, an easy-to-use and freely available software program, designed by the thesis author (BFM), has been made available at http://www.rehabtools.org/hand-held-dynamometer.html to assist clinicians in the assessment of isometric power using HHD. It should also be noted that extra padding was secured to the Lafayette HHD to protect the stroke cohort for any potential pain or abrasion. Clinicians may wish to also attach similar foam padding to protect their patients from any discomfort. The low sampling frequency of the HHDs used in the current study may limit their use in future research for calculation of RFD or RTD, however it was deemed appropriate to use in the current thesis to examine the ability of this inexpensive and easy-to-use device. Future research may benefit from this low cost alternative to the expensive and difficult equipment that is commonly used in projects to assess strength and power.

This program of research also examined how measures of isometric strength and power obtained from HHD related with measures of gait function following stroke. The comparison between isometric strength and power revealed that isometric strength explained more of the variance in gait following stroke compared with isometric power. When considering gait function following stroke it may be efficient to examine measures of isometric strength, as obtaining isometric power using currently available HHD requires post-processing of the

time series of the raw force data. It should be noted that, despite this thesis suggesting that isometric strength is more important for gait function compared with isometric muscle power, other measures of dynamic power may still provide important information about gait function following stroke.

This program of research also analysed multiple lower limb muscle groups to investigate which one had the strongest relationship with gait velocity following stroke. For gait velocity, the ankle plantarflexors and hip flexors demonstrated the strongest relationship in the stroke population. These two muscle groups provide a large amount of the joint power generation during gait (Kepple et al., 1997; Liu et al., 2006; Neptune et al., 2004). When examining joint power generation during gait, isometric ankle plantarflexor strength showed a strong correlation with peak ankle joint power generation. This indicates that assessment of isometric ankle plantarflexor strength may be considered during stroke rehabilitation due to the strong correlations with gait function.

The knee extensor muscle group, which is commonly assessed and treated in clinical and research settings for neurological rehabilitation (Williams et al., 2014b), showed poor relationships in this thesis with gait velocity and joint power generation during gait. It is interesting that knee extensor strength has previously been the focus of assessment and treatment during stroke rehabilitation. This may be due to numerous reasons with one potential explanation being that laboratory-based dynamometers are often configured for the assessment of knee extensor strength, with extra attachments and position changes required to assess hip or ankle strength. A previous systematic review found that the majority of strength training interventions in neurological rehabilitation focus on knee extensor strength and that these interventions fail to improve gait function (Williams et al., 2014b). Clinicians need to examine the strength of multiple lower limb muscle groups in post-stroke

rehabilitation when considering gait velocity, as this thesis combined with previous research suggests that the strength of the knee extensors play a limited role in gait function following stroke.

The work contained within this thesis can be used to help inform the development of future intervention strategies. The results of the regression analyses suggest that clinicians may wish to consider targeting the assessment and treatment of the strength of the ankle plantarflexors and hip flexors. Further research is needed to determine the effects that specific training to improve ankle plantarflexor or hip flexor strength has on gait function post-stroke, however this program of research can assist in shifting the clinical focus to target these potentially important muscle groups.

7.3 Strengths and limitations

This thesis has provided a detailed analysis of the relationship between measures of isometric strength and power with gait function following stroke. The first two studies incorporated a detailed systematic review for Study One and a thorough analysis of the psychometric properties of HHD for assessment of lower limb isometric strength and power for Study Two. Study Two was the first study to examine the use of HHD for assessment of RFD. This study involved a comparison between two assessors, different versions of HHD and multiple methods of RFD calculation. This ensured a complete analysis of the reliability and validity of HHDs to ensure the devices and methods used in the subsequent studies were psychometrically-sound. These first two studies provided the basis for the subsequent two studies in a stroke population.

The final two studies included an international multi-centre study examining the relationships between HHD measures of strength and power with gait after stroke. This

program of research examined the measurement of isometric power, which is a measure that is rarely used in the stroke population and has never previously been measured with HHD. Study Three included a relatively large sample size of 63 and assessed seven lower limb muscle groups. The majority of studies identified in Study One had less than 35 participants (14/21 studies) and only one study assessed more than two lower limb muscle groups with a sample size above 40 participants (Dorsch et al., 2012). Other strengths of Study Three were that it incorporated a detailed description of participant characteristics as well as examined the test-retest reliability of HHD measures of isometric strength and RTD in a subset of participants (both rarely done in those studies identified in Study One). Study Four assessed the relationship between HHD measures and joint power generation during gait, which has been assessed previously in other neurological populations (Dallmeijer et al., 2011; Kahn & Williams, 2015). Prior to this thesis, this relationship had not been examined in the stroke population. In contrast with the previous studies in other neurological populations (Dallmeijer et al., 2011; Kahn & Williams, 2015), Study Four included a HHD assessor that showed acceptable psychometric properties when using HHD and provided strength scores normalised to body mass. Overall, this thesis may help to guide the assessment and treatment plan for clinicians and create a solid platform for future research.

This thesis is not without limitations. It would be erroneous to imply that the muscle groups of the lower limb work in isolation and that a lack of strength in one muscle group is solely responsible for a reduction in gait function. It should also be noted that correlations do not indicate causation and therefore improvements in muscle strength or power do not necessarily result in subsequent improvements in gait function following stroke. In order to effectively and optimally improve gait velocity after stroke, it may be pertinent to understand the impairments that contribute to reduced gait velocity. Consequently, this thesis was warranted to understand the relationship between isometric muscle function and gait

following stroke. This program of research showed a strong relationship between isometric strength of the ankle plantarflexors and hip flexors with gait velocity, while the understanding of this relationship may be improved through examining non-linear relationships.

The population recruited for Study Two was a young and healthy population, with the results of Study Two not necessarily being applicable to clinical populations. The inclusion of a healthy population was necessary for Study Two due to the large time and effort demands of assessment. The choice of the criterion-reference laboratory-based dynamometer for Study Two may also be seen as a limitation, especially when considering the lower concurrent validity results for the measurement of the ankle.

The protocol used in this thesis for the measurement of isometric strength and RTD may not be representative of the joint positions or the dynamic muscle contractions seen during gait. The testing positions were chosen to minimise the required amount of position changes for the participants as well as to reduce the time demands of testing. Although some of the testing positions included joint angles that are not seen during gait, the chosen positions showed acceptable psychometric properties in Study Two and Study Three. Additionally, the isometric nature of assessment may not necessarily be reflective of the dynamic contractions during gait. Strength or power measures that are more representative of the quick and submaximal contractions seen during walking may have stronger associations with gait velocity following stroke. However, Study Three and Four did find strong correlations between isometric strength and gait, indicating that the assessment of isometric strength is still warranted for clinical and research purposes.

7.4 Future directions

This program of research aimed to examine a clinically feasible device (HHDs) for measurement of isometric lower limb muscle function and how such measures related to gait following stroke. The measurement of isometric ankle plantarflexor strength with HHD showed strong associations with gait velocity and peak APG during gait. This highlights the potential for further examination of isometric ankle plantarflexor strength following stroke when considering post-stroke gait. This program of research could also inform the design of intervention strategies to target improvements in ankle strength to potentially also improve gait function following stroke. Future interventions need to be developed that target specific muscle groups, such as the ankle plantarflexors and hip flexors, and train the muscle groups in the manner in which they act during gait (e.g. ankle plantarflexor spring mechanism) to potentially result in improvements in gait following stroke.

A recent systematic review showed that many previous interventions in neurological rehabilitation that aim to improve gait often focus on solely training the strength of the knee extensors, with the authors of the review suggesting that other muscle groups that are more important for producing forward progression during gait need to be trained (Williams et al., 2014b). This program of research lends support to that suggestion. The strength and RTD of the knee extensors showed lower correlation values compared with other lower limb muscle groups throughout the studies in this thesis. Future research that considers post-stroke gait may wish to assess and treat the strength of other lower limb muscle groups rather than just solely the strength of the knee extensors.

This thesis used cross-sectional research designs to examine the relationship between gait velocity and HHD measures of strength and RTD. Future research may examine how these measures change over time following stroke and how the relationship changes during post-

stroke rehabilitation. Longitudinal research designs would be required to monitor these changes to examine the correlation between improvements in gait velocity and isometric strength or RTD. Future research may also examine the responsiveness of measures of strength and RTD from HHD.

Whilst previous work has commented on the potential difficulties when measuring ankle plantarflexor strength with HHD (Robinson, 2015), this method currently provides the most suitable measure of isometric ankle plantarflexor strength in a clinical setting. Prior to this thesis, HHD had never been used for the assessment of RTD. Study Two revealed that HHD demonstrated mostly acceptable psychometric properties, highlighting promise for the use of HHD for assessment of isometric strength and RTD. Although Study Two only involved an unimpaired population, the results lend support to the use of HHD for assessment of RTD in other clinical populations. Previous research has highlighted the importance of RTD in populations such as cerebral palsy and knee osteoarthritis (Hsieh et al., 2015; Moreau et al., 2012; Winters et al., 2014; Winters & Rudolph, 2014). Further research is needed to assess the ability of HHD to be used in other populations to reliably assess RTD and how this measure relates to different impairments and limitations in various clinical populations.

It should be noted that the results from Study Two suggest potentially low concurrent validity of HHD for assessment of isometric ankle strength and RTD compared with a fixed, laboratory-based dynamometer. Previous research has used custom-built rigs to assess isometric strength and RTD (De Ruiter, Van Leeuwen, Heijblom, Bobbert, & De Haan, 2006; Folland, Buckthorpe, & Hannah, 2014; Ng & Hui-Chan, 2005, 2012), which could potentially improve the validity of ankle assessment from HHDs compared to the laboratory-based fixed dynamometer used in this thesis. Recent research has recommended using rigid custom-built dynamometers for assessment of RTD (Maffiuletti et al., 2016). Further

research is needed to determine the validity of ankle assessment from HHDs, when compared to other dynamometers.

The results from this program of research also suggest that the RTD measured with HHD did not provide any significant value over measures of isometric strength in the relationship with gait function following stroke. This was an interesting finding, especially when considering gait requires quick and submaximal contractions (i.e. power), rather than slow and maximal contractions (i.e. strength). It was anticipated that measures of RTD would provide stronger relationships with gait over strength, due to the previous studies showing RTD had a stronger relationship over strength (Moreau et al., 2012; Pohl et al., 2002; Winters & Rudolph, 2014). Although the results of this thesis suggest isometric strength had a stronger relationship with gait compared with isometric RTD, measurement and treatment of muscle power is still warranted in stroke rehabilitation. Dynamic measures of muscle power using pneumatic resistance machines may explain more of the variance in gait velocity compared with muscle strength in other clinical populations including mobility limited older people and those with Parkinson's disease (Allen et al., 2010; Bean et al., 2002; Cuoco et al., 2004; Sayers et al., 2005). Dynamic measures of power may provide a stronger link with gait compared with muscle strength, although further research is required in the stroke population. As calculation of RTD is done from an isometric MVC, measures that mimic the action of the ankle plantarflexors during gait (a spring or catapult action) may provide a stronger association with gait and need further investigation.

7.5 Conclusions

The overall aim of this thesis was to provide a comprehensive analysis of how lower limb isometric muscle function is associated with gait following stroke. This thesis used clinically feasible HHD for the assessment of isometric strength and power to determine how these

measures related to clinical (gait velocity) and laboratory (joint power generation) measured gait function. Specific aims were to determine which lower limb muscle group had the strongest relationship with gait and to compare isometric strength and power to determine which measure had a stronger relationship with gait following stroke.

The main conclusions from each study are:

1. Systematic review (Study One, Chapter 3)
    i. The strength of the ankle dorsiflexors appear to provide the strongest correlation with gait velocity following stroke;
    ii. Caution is needed when interpreting the results of the systematic review as the majority of included studies had small sample sizes and lacked adequate methodological quality;
    iii. The systematic review highlighted the need for further research to examine the associations between isometric strength and gait velocity after stroke.
2. Psychometric properties of HHD (Study Two, Chapter 4)
    i. Hand-held dynamometry had acceptable test-retest and inter-rater reliability as well as concurrent validity for the assessment of isometric strength and power in an unimpaired cohort;
    ii. Lower than expected concurrent validity was shown for isometric measures of ankle strength and power, however this may be due to the attachment used on the laboratory-based fixed dynamometer;
    iii. Hand-held dynamometry provides a clinically feasible measure of isometric strength and power with relatively low cost and minimal time requirements.
3. Associations of isometric strength/power and gait velocity (Study Three, Chapter 5)

i. Hand-held dynamometers possess good to excellent test-retest reliability for the assessment of lower limb isometric strength and power following stroke;
ii. Both measures of isometric strength and power had significant associations with gait velocity after stroke;
iii. Comparison between measures revealed isometric strength to explain more of the variance in gait velocity over and above measures of isometric power;
iv. The strength of the ankle plantarflexors and hip flexors had the strongest relationship with gait velocity.

4. Hand-held dynamometry relationship with joint power generation during gait (Study Four, Chapter 6)
    i. Measures of knee and hip isometric muscle function did not show significant relationships with knee and hip power generation during gait;
    ii. Isometric strength had a stronger relationship with joint power generation during gait compared with isometric power following stroke;
    iii. Isometric ankle plantarflexor strength had significant moderate to good correlations with peak ankle power generation during gait after stroke.

The previous literature had significant gaps that limited the ability to comprehensively examine the associations between muscle function and gait following stroke. Whilst further research is needed that involves different measures of muscle power and new intervention strategies to improve gait, this program of research has formed a solid foundation that will allow future research to further examine the role muscle strength and power has on gait function as well as to inform the future implementation of targeted interventions to improve gait following stroke. It is anticipated that the results from this thesis will aid in the design of future research as well as to help clinicians in their clinical decision making regarding rehabilitation of lower limb strength, power and gait following stroke.

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CHAPTER NINE: APPENDICES

Appendix A – Extra results from Study One

Additional description for Figure 3.2 (adapted with permission from Mentiplay et al. (2015a)). To ensure the figure is as clear as possible, there were restrictions on studies reporting multiple correlations of similar variables. The variable chosen for reporting in the figure was based on a series of decision rules, specifically:

1. When studies provided a correlation to gait velocity for both normalised and non-normalised strength (Bohannon, 1991; Nadeau et al., 1997; Severinsen et al., 2011), only the normalised strength correlations were included in the figure as normalised strength provides a better indication of an individual's strength relative to their physical characteristics.
2. When studies provided correlations between gait velocity and strength measured over multiple sessions (Bohannon, 1989b; Bohannon & Andrews, 1990), only the initial assessment was included.
3. When studies provided strength measures at multiple knee joint angles (Nakamura et al., 1985), we included only the tests performed with the knee joint at 90° as the majority of studies used this joint angle during assessment.
4. When studies included correlation values of multiple measures of strength (e.g. force and torque (Bohannon, 1991), we included only measures of force in the figure.
5. When studies included correlations between isometric strength and gait velocity performed at a comfortable and fast pace (Bohannon, 1992; Bohannon & Walsh, 1992; Nadeau et al., 1997), we only included fast paced gait in the figure as to only report one correlation for the same study.

Appendix Table 1. Associations between gait velocity and isometric lower limb strength following stroke

Article	Gait test	Gait speed	Strength device	Muscles tested	Position of testing	Sample size	Correlation to gait velocity (N - P)	Correlation to gait velocity (nN - P)	Correlation to gait velocity (N - nP)	Correlation to gait velocity (nN - nP)
Bohannon 1986a	8m walk	CGS	HHD†	HF, HE, HAB, KE, KF, AP, AD	HF/HE – Hip flexed to 90° HAB – Hip extended KE/KF – Knee flexed to 90° AP/AD – ankle at 90°	20	HF: 0.252 HE: 0.595* HAB: 0.419 KE: 0.357 KF: 0.466* AP: 0.468* AD: 0.559*	--	--	--
Bohannon 1989a	8m walk	CGS	HHD	KE	KE – knee at 90°	12	--	KE: 0.702	--	KE: 0.545
Bohannon 1989b	8m walk	CGS	HHD†‡ (measured twice, initial values provided)	HF, HE, HAB, KE, KF, AP, AD	HF/HE – Hip flexed to 90° HAB – Hip extended KE/KF – Knee flexed to 90° AP/AD – ankle at 90°	33	HF: 0.815*** HE: 0.776*** HAB: 0.799*** KE: 0.813*** KF: 0.826*** AP: 0.827*** AD: 0.769***	--	HF: 0.514** HE: 0.410 HAB: 0.511** KE: 0.568*** KF: 0.423 AP: 0.438 AD: 0.427	--
Bohannon 1991	8m walk	CGS	HHD† (Force) (cTorq) and Cybex (mTorq)	KE	KE – knee at 95°	26	KE Force: 0.616*** KE cTorq: 0.654*** KE mTorq: 0.677***	KE Force: 0.603** KE cTorq: 0.629*** KE mTorq: 0.654***	KE Force: 0.052 KE cTorq: 0.141 KE mTorq: 0.200	KE Force: 0.147 KE cTorq: 0.196 KE mTorq: 0.245
Bohannon 1992	7m walk	CGS & FGS	Lido Active	KE	KE – knee at 90°	20	--	KE-CGS: 0.747*** KE-FGS: 0.744***	--	KE-CGS: 0.524* KE-FGS: 0.448*

Bohannon & Andrews 1990	8m walk	CGS	Cybex‡ (measured on 2 days, twice each day)	KE	KE – knee at 90°	17	--	KE d1m1: 0.605* KE d1m2: 0.539* KE d2m1: 0.564* KE d2m2: 0.575*	--	--
Bohannon & Walsh 1992	7m walk	CGS & FGS	Lido Active	KE	KE – knee at 90°	14	--	KE-CGS: 0.667** KE-FGS: 0.755**	--	KE-CGS: 0.467 KE-FGS: 0.499
Davies et al 1996	10m walk	FGS	Lido Active	KE	Knee at 90°	12	--	KE: 0.56	--	--
Dorsch et al 2012	10m walk	CGS	HHD†	HF, HE, HIR, HER, HAB, HAD, KE, KF, AP, AD, AI, AE	HF/HIR, HER/HAB, KE/KF. AP/AD, AI/AE – Hips and Knee at 90° HE – Hip at 0° HAD – Hip and knee in flexion with foot resting on plinth	60	HF: 0.35* HE: 0.29* HIR: 0.30* HER: 0.22 HAB: 0.24 HAD: 0.29* KE: 0.27* KF: 0.30* AP: 0.29* AD: 0.50** AI: 0.25 AE: 0.33*	--	--	--
Horstman et al 2008	10m walk	CGS	LEXS	KE, KF	KE/KF – Knee at 60°	14§	--	KE: -0.545 KF: -0.763**	--	KE: -0.699* KF: -0.634*
Kobayashi et al 2011	5m walk	FGS	HHD	KE	KE – Knee at 90°	10	--	KE: 0.459*	--	--
Lam et al 2010	6m walk	CGS	HHD†	KE	KE – Knee at 90°	45	KE: 0.55**	--	--	--

Lin et al 2006	GAITRite	CGS	HHD†	AP, AD	Ankle in neutral	68	AP: 0.58** AD: 0.67**	--	--	--
Lin 2005	10m walk (3DGA)	CGS	HHD†	HF, KE, AD	Standardised to previous protocol	21	HF: 0.633** KE: 0.436* AD: 0.645**	--	--	--
Liu-Ambrose et al 2007	10m walk	CGS	HHD‖	KE	Knee at 90°	63	KE: 0.35**	--	KE: 0.15	--
Maeda et al 2000	10m walk	FGS	HHD	KE	Sitting position	40	--	M KE: -0.42** F KE: -0.33	--	M KE: -0.41** F KE: -0.43**
Nadeau et al 1997	9m walk	CGS & FGS	Biodex†	AP	Ankle at 10° of AP	16	AP-CGS: 0.25 AP-FGS: 0.29	AP-CGS: 0.11 AP-FGS: 0.18	--	--
Nakamura et al 1985	10m walk	FGS	Cybex (Isometric at 3 knee angles)	KE	KE – Knee at 30°, 60° and 90°	11	--	KE90: 0.759** KE60: 0.749** KE30: 0.595	--	KE90: 0.436 KE60: 0.195 KE30: 0.175
Nasciutti-Prudente et al 2009	10m walk	CGS	HHD	HF, HE, KE, KF, AP, AD	HF, KE, AD – Seated position HE, KF, AP – Lying prone	12	--	HF: 0.75* HE: 0.53 KE: 0.34 KF: 0.80* AP: 0.58* AD: 0.50	--	HF: 0.26 HE: 0.38 KE: 0.19 KF: 0.34 AP: 0.45 AD: -0.13
Ng & Hui-Chan 2012	GAITRite	CGS	Load Cell mounted on a foot frame	AP, AD	Ankle in neutral position	62	--	AP: 0.318* AD: 0.727**	--	--
Severinsen et al 2011	10m walk¶	CGS	Biodex¶	KE	Knee extended	48	KE: 0.31*	KE: 0.18	--	--

Note: N = normalised; nN = not normalised; P = paretic limb; nP = non-paretic limb; CGS = comfortable gait speed; FGS = fast gait speed; HHD = hand-held dynamometer; Lido Active = Lido Active Rehabilitation System; LEXS = lower extremity system; Cybex = Cybex isokinetic dynamometer; Biodex = Biodex system dynamometer; 3DGA = three-dimensional gait analysis; GAITRite = GAITRite walkway system; cTorq

= calculated torque; mTorq = measured torque; M = male; F = female; HF = hip flexors; HE = hip extensors; HIR = hip internal rotators; HER = hip external rotators; HAB = hip abductors; HAD = hip adductors; KE = knee extensors; KF = knee flexors; AP = ankle plantarflexors; AD = ankle dorsiflexors; AI = ankle invertors; AE = ankle evertors; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; † = normalised to body mass; ‡ = measured on multiple days, only initial assessment correlation is reported here; § = three participants could not perform gait test hence were not used for analysis; || = normalised to body mass and height; ¶ = normalised to expected value using age, height and sex adjusted regression equations from healthy populations; -- = not measured. Table adapted with permission from Mentiplay et al. (2015a).

Appendix B – Extra results from Study Two

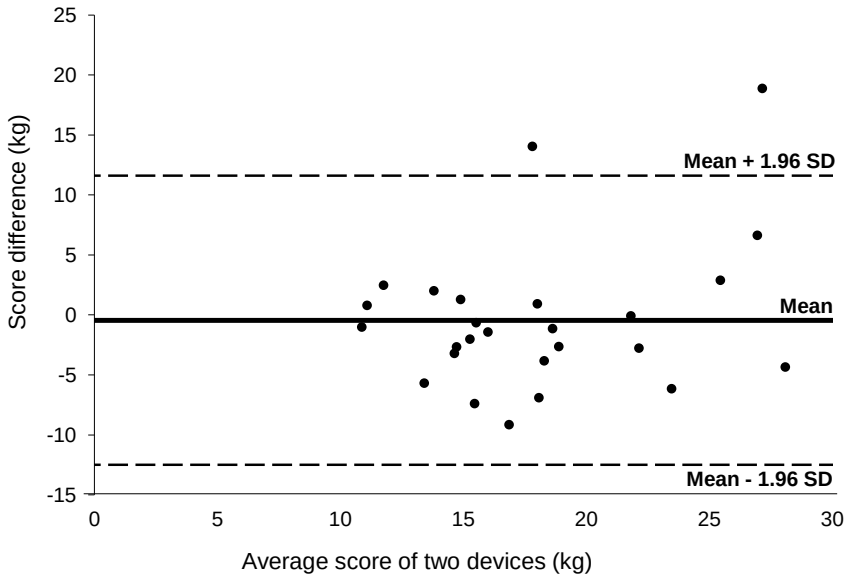
Bland-Altman Plots for the validity of the HHDs in comparison with the KinCom

Note: Not all reliability and validity analyses include 30 data sets. Some participants mentioned soreness in some muscle groups unrelated to the testing procedures, and consequently those sore muscles were not tested. The knee extensors and ankle plantarflexors of one participant were unable to be tested due to high strength and power levels of the participant. One participant was unable to attend the second testing session. The KinCom was unable to be used at all for four participants as the device was being repaired and five participants only had one session of KinCom data collection. On many occasions the Hoggan software failed to save the raw data during testing, resulting in fewer data sets for all analyses involving the Hoggan device. The parentheses prior to each figure details the number of participants that were used for analysis. These Bland-Altman plots are replicated with permission from Mentiplay et al. (2015b).

1. Lafayette Peak Force (kg)

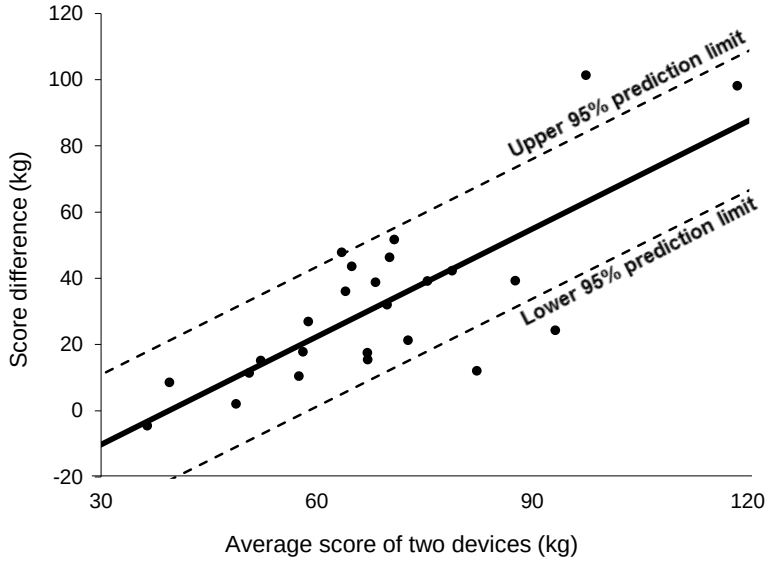
Assessor-A ankle dorsiflexors (Lafayette peak force):

(n: validity = 26; Lafayette intra-rater reliability = 29; KinCom reliability = 19; inter-rater reliability = 29; inter-device reliability = 27)



Assessor-A ankle plantarflexors (Lafayette peak force):

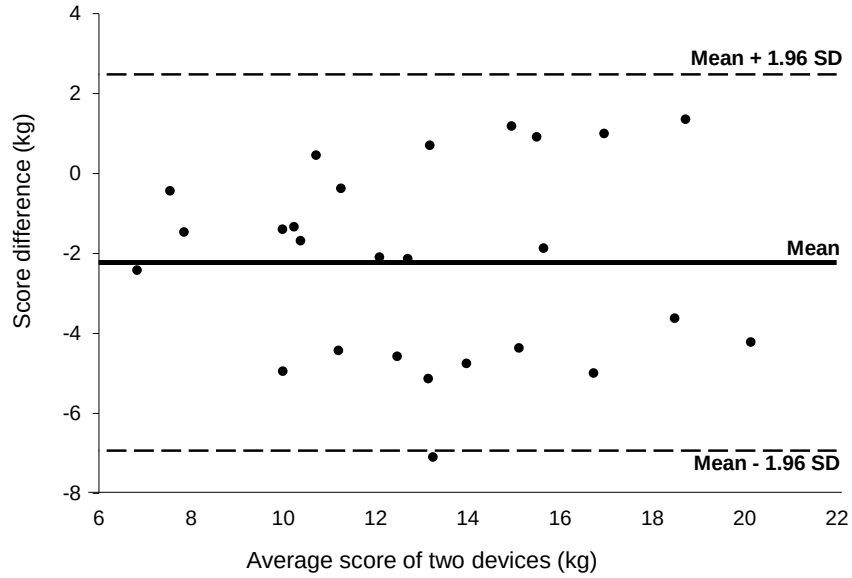
(n: validity = 25; Lafayette intra-rater reliability = 28; KinCom reliability = 20; inter-rater reliability = 29; inter-device reliability = 27)



R = 0.77**; R^2** = 0.59**; Slope** = 1.08**; Intercept** = -42.68

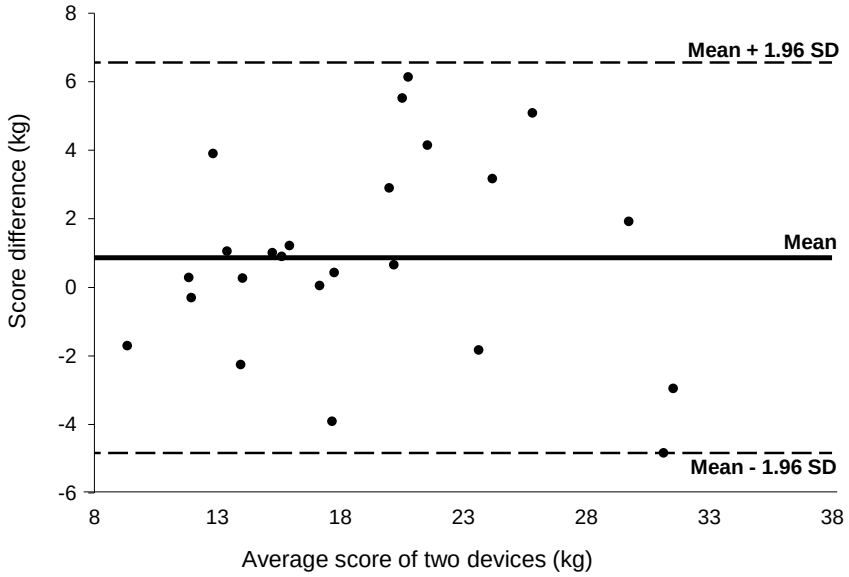
Assessor-A hip abductors (Lafayette peak force):

(n: validity = 26; Lafayette intra-rater reliability = 29; KinCom reliability = 20; inter-rater reliability = 30; inter-device reliability = 28)



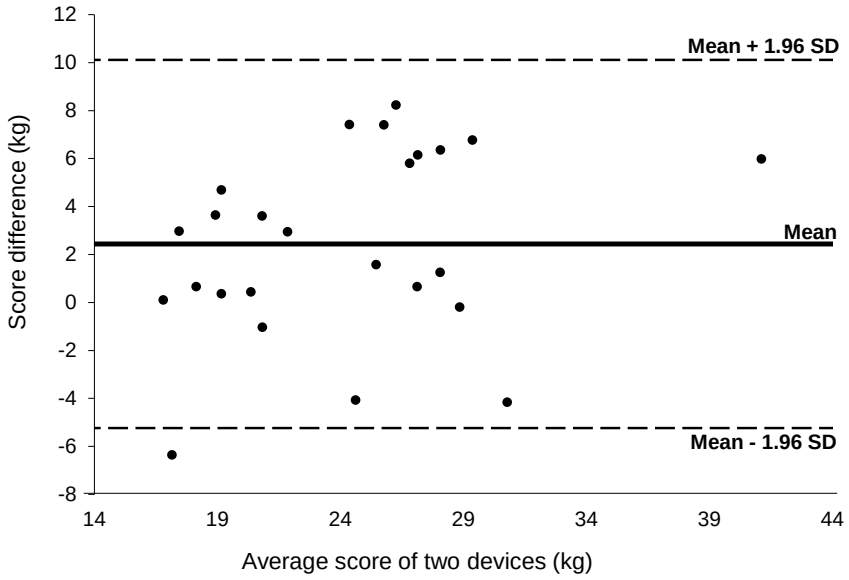
Assessor-A hip adductors (Lafayette peak force):

(n: validity = 24; Lafayette intra-rater reliability = 27; KinCom reliability = 18; inter-rater reliability = 28; inter-device reliability = 24)



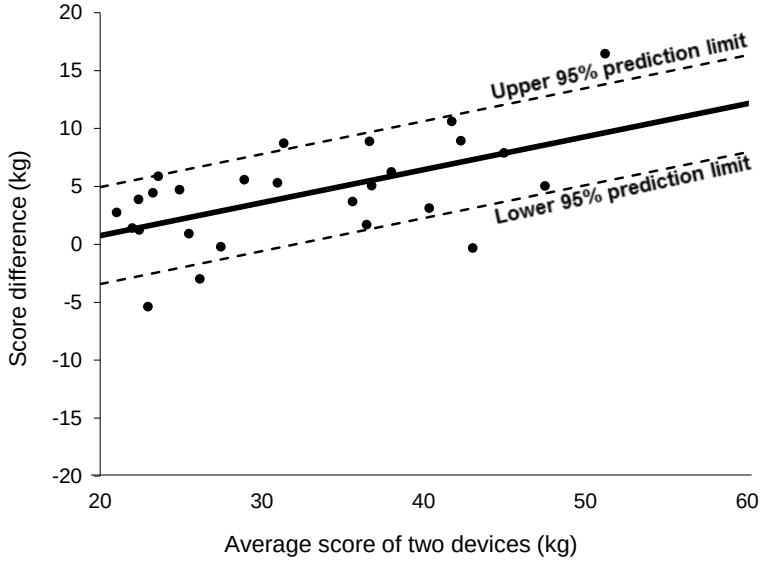
Assessor-A hip extensors (Lafayette peak force):

(n: validity = 25; Lafayette intra-rater reliability = 28; KinCom reliability = 20; inter-rater reliability = 30; inter-device reliability = 29)



Assessor-A hip flexors (Lafayette peak force):

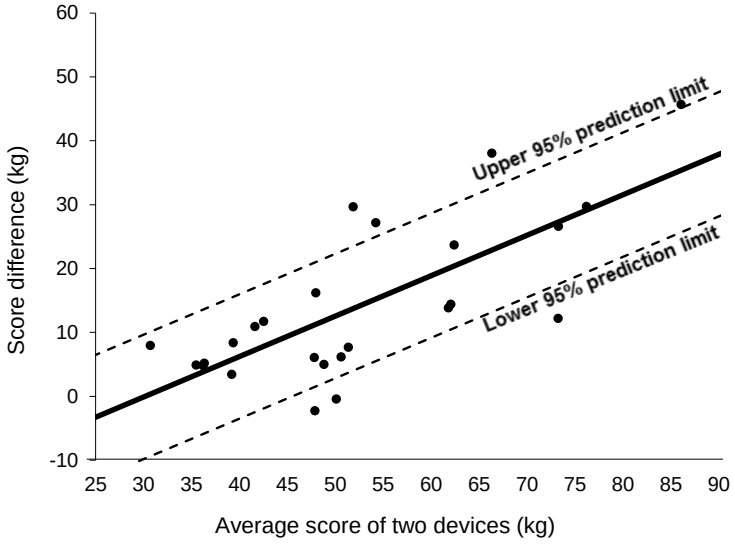
(n: validity = 26; Lafayette intra-rater reliability = 29; KinCom reliability = 20; inter-rater reliability = 30; inter-device reliability = 25)



R = 0.58**; R^2** = 0.33**; Slope** = 0.28**; Intercept** = -4.92

Assessor-A knee extensors (Lafayette peak force):

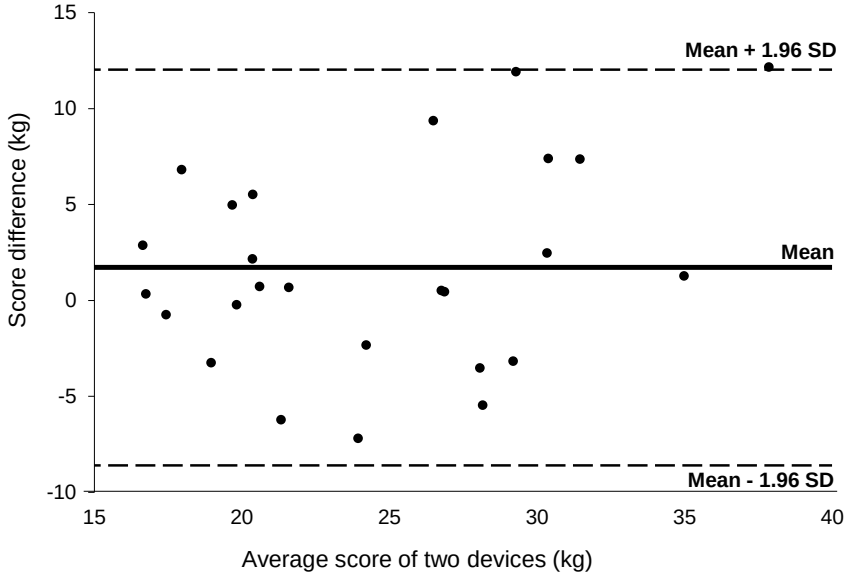
(n: validity = 25; Lafayette intra-rater reliability = 27; KinCom reliability = 20; inter-rater reliability = 27; inter-device reliability = 25)



R = 0.74**; R^2** = 0.54**; Slope** = 0.63**; Intercept** = -19.04

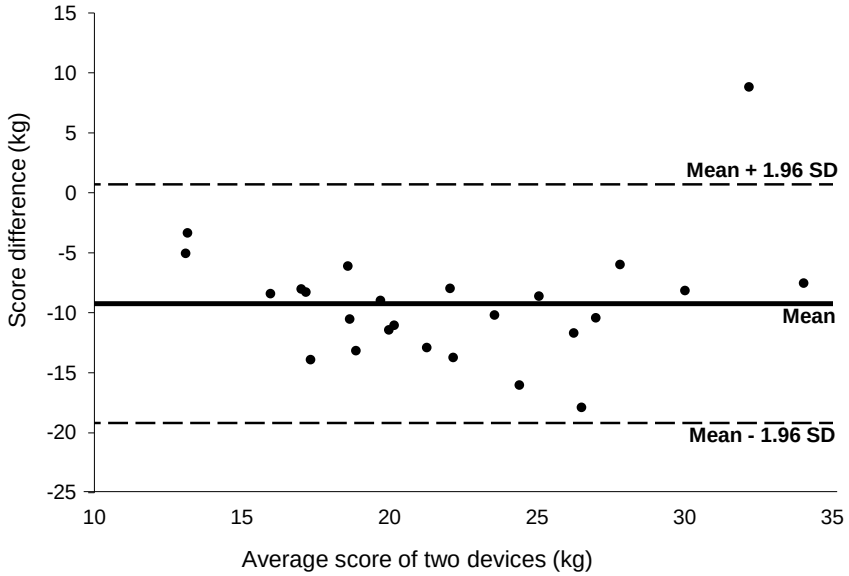
Assessor-A knee flexors (Lafayette peak force):

(n: validity = 26; Lafayette intra-rater reliability = 29; KinCom reliability = 20; inter-rater reliability = 30; inter-device reliability = 20)



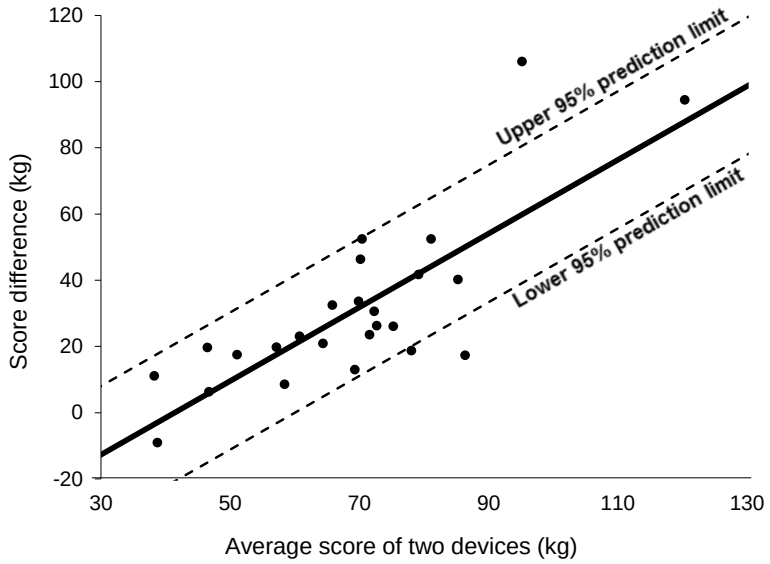
Assessor-B ankle dorsiflexors (Lafayette peak force):

(n: validity = 25; Lafayette intra-rater reliability = 28; inter-device reliability = 27)



Assessor-B ankle plantarflexors (Lafayette peak force):

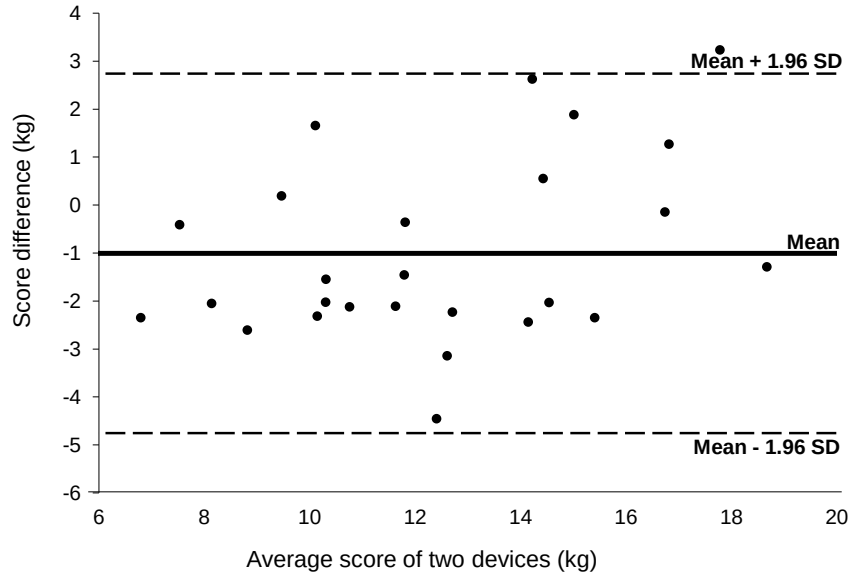
(n: validity = 25; Lafayette intra-rater reliability = 28; inter-device reliability = 27)



R = 0.79**; R^2** = 0.63**; Slope** = 1.11**; Intercept** = -45.97

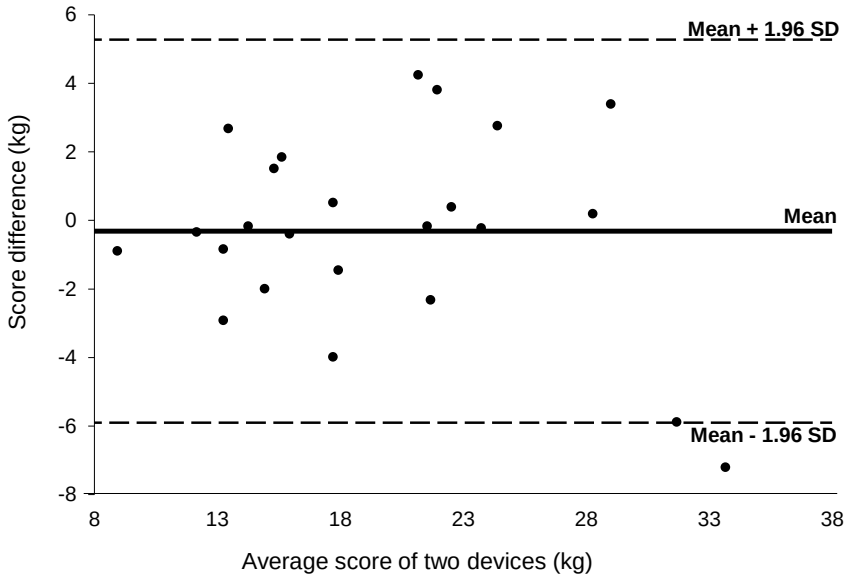
Assessor-B hip abductors (Lafayette peak force):

(n: validity = 26; Lafayette intra-rater reliability = 29; inter-device reliability = 28)



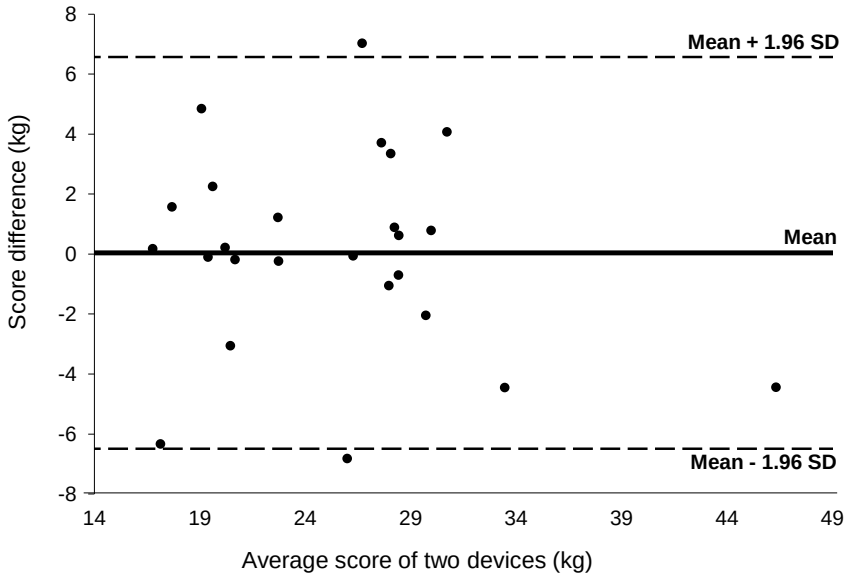
Assessor-B hip adductors (Lafayette peak force):

(n: validity = 24; Lafayette intra-rater reliability = 27; inter-device reliability = 26)



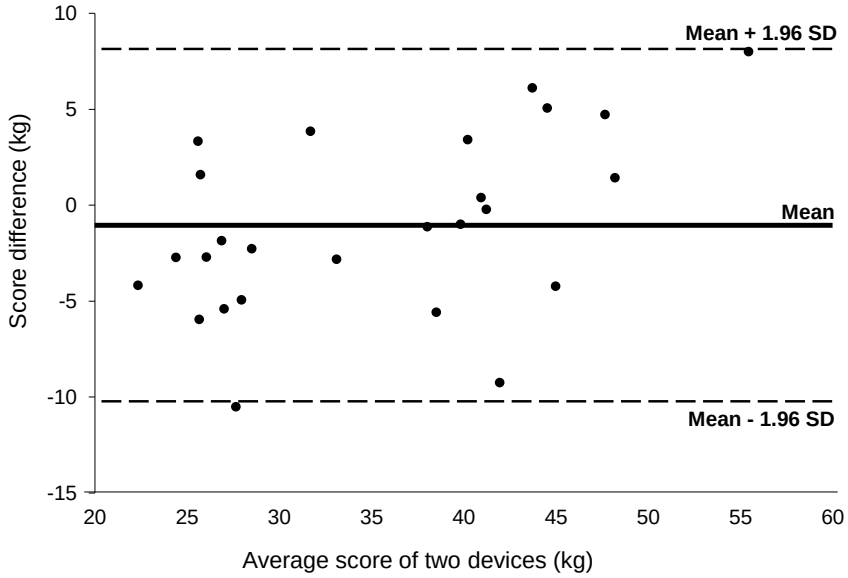
Assessor-B hip extensors (Lafayette peak force):

(n: validity = 25; Lafayette intra-rater reliability = 28; inter-device reliability = 27)



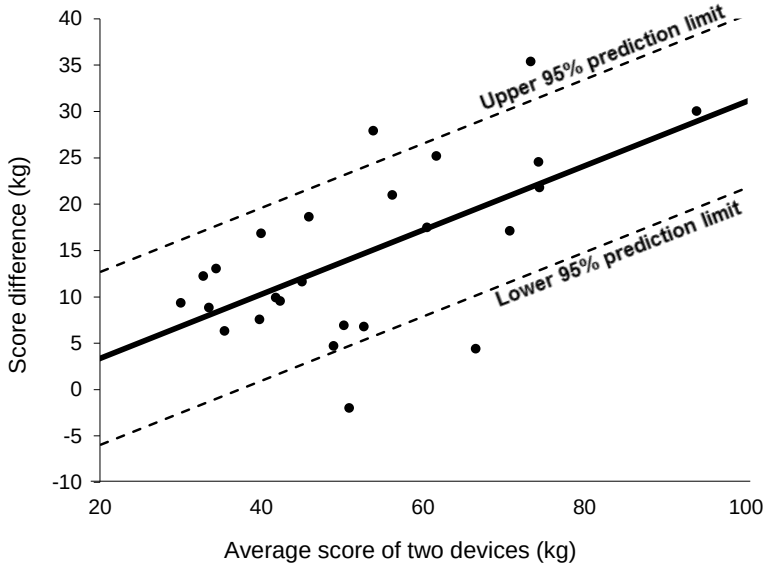
Assessor-B hip flexors (Lafayette peak force):

(n: validity = 26; Lafayette intra-rater reliability = 29; inter-device reliability = 27)



Assessor-B knee extensors (Lafayette peak force):

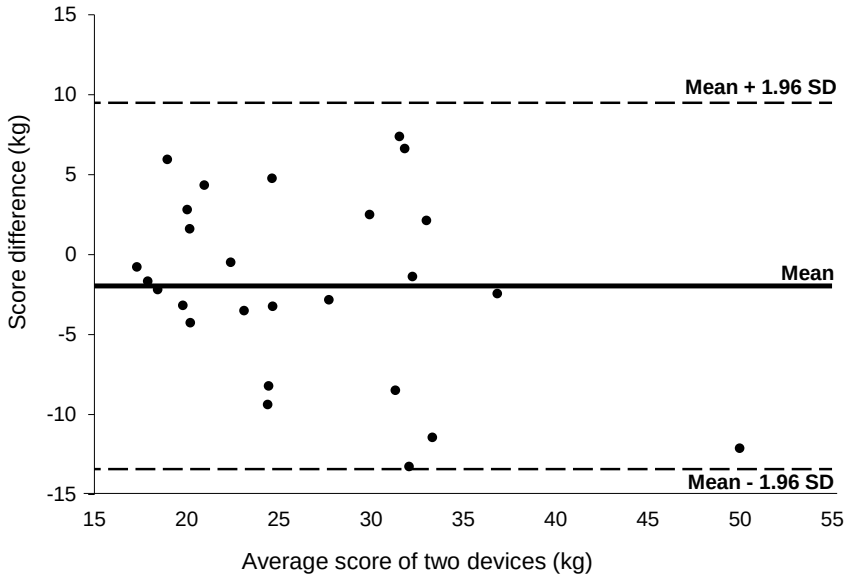
(n: validity = 25; Lafayette intra-rater reliability = 28; inter-device reliability = 28)



R = 0.61**; R^2** = 0.37**; Slope** = 0.35**; Intercept** = -3.55

Assessor-B knee flexors (Lafayette peak force):

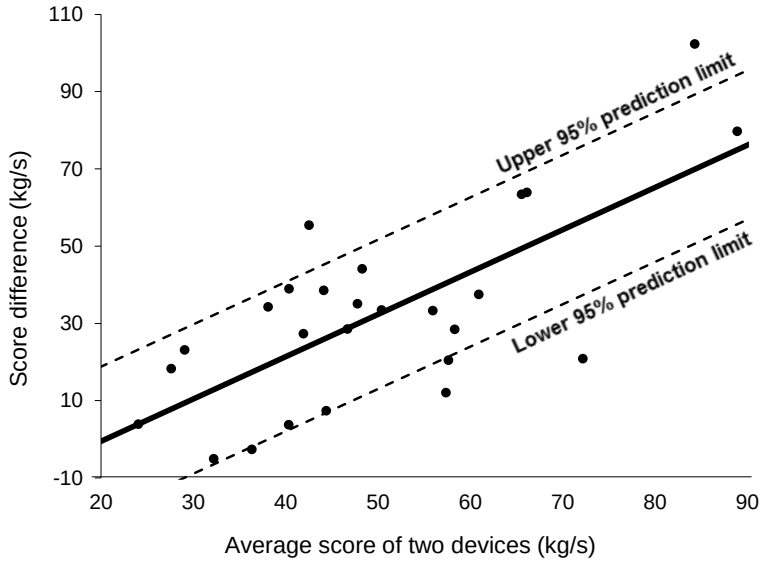
(n: validity = 26; Lafayette intra-rater reliability = 29; inter-device reliability = 24)



2. Lafayette RFD (kg/s)

Assessor-A ankle dorsiflexors (Lafayette RFD):

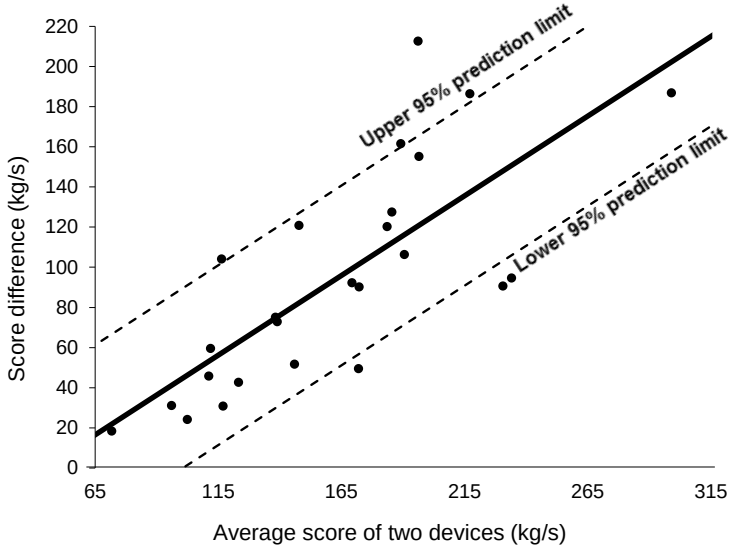
(n: validity = 26; Lafayette intra-rater reliability = 29; KinCom reliability = 19; inter-rater reliability = 29; inter-device reliability = 27)



R = 0.71**; R^2** = 0.51**; Slope** = 1.10**; Intercept** = -22.37

Assessor-A ankle plantarflexors (Lafayette RFD):

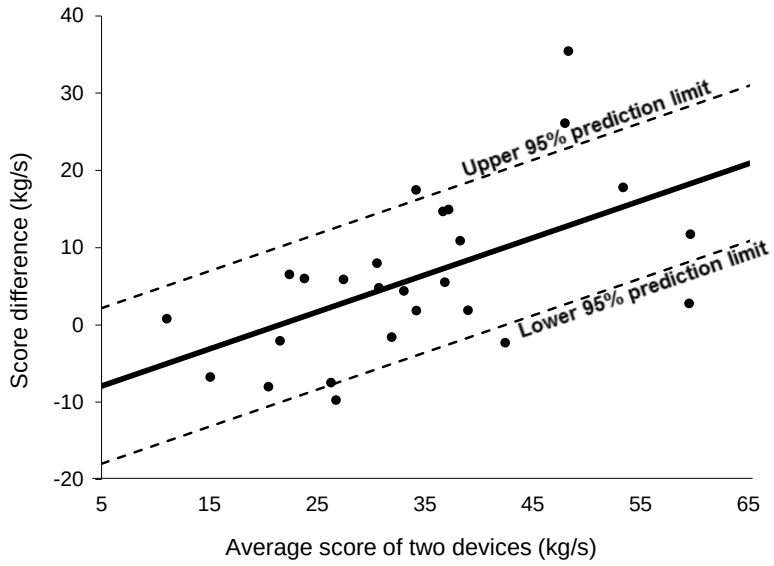
(n: validity = 25; Lafayette intra-rater reliability = 28; KinCom reliability = 20; inter-rater reliability = 29; inter-device reliability = 27)



R = 0.76**; R^2** = 0.57**; Slope** = 0.79**; Intercept** = -34.90

Assessor-A hip abductors (Lafayette RFD):

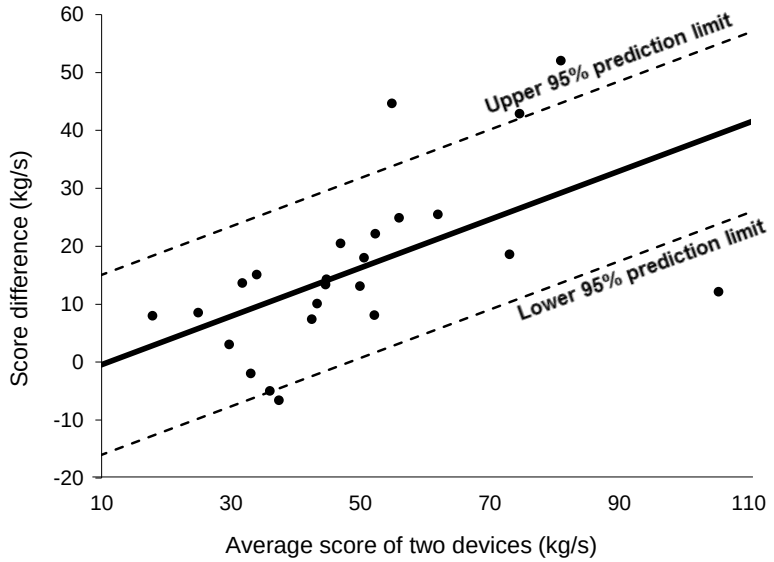
(n: validity = 26; Lafayette intra-rater reliability = 29; KinCom reliability = 20; inter-rater reliability = 30; inter-device reliability = 28)



R = 0.56**; R^2** = 0.32**; Slope** = 0.48**; Intercept** = -10.28

Assessor-A hip adductors (Lafayette RFD):

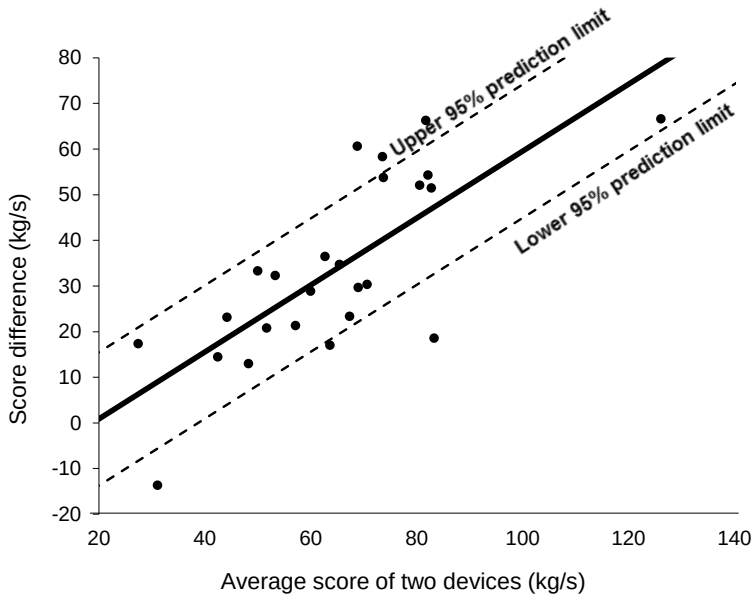
(n: validity = 24; Lafayette intra-rater reliability = 27; KinCom reliability = 18; inter-rater reliability = 28; inter-device reliability = 24)



R = 0.56**; R^2** = 0.32**; Slope** = 0.42**; Intercept** = -4.62

Assessor-A hip extensors (Lafayette RFD):

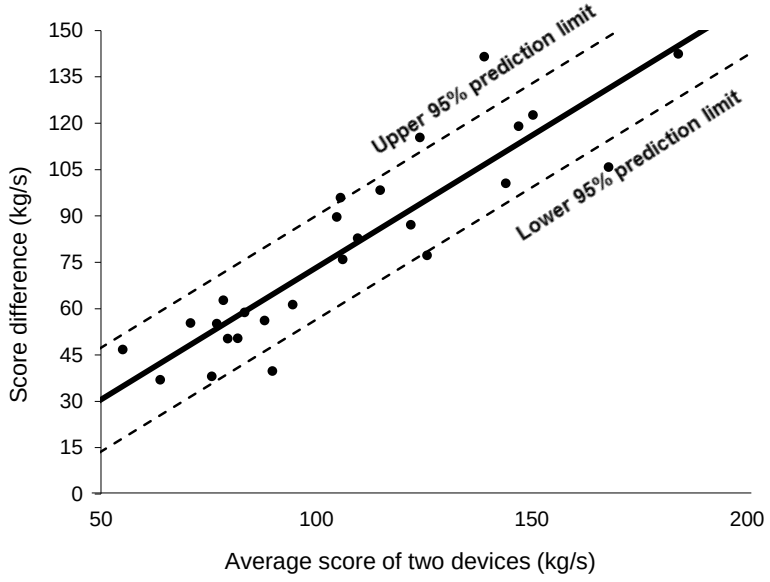
(n: validity = 25; Lafayette intra-rater reliability = 28; KinCom reliability = 20; inter-rater reliability = 30; inter-device reliability = 29)



R = 0.75**; R^2** = 0.56**; Slope** = 0.73**; Intercept** = -13.71

Assessor-A hip flexors (Lafayette RFD):

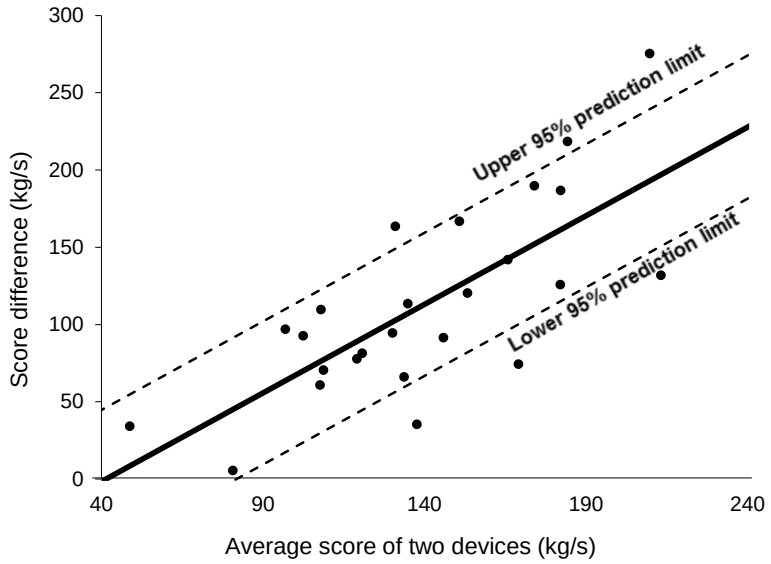
(n: validity = 26; Lafayette intra-rater reliability = 29; KinCom reliability = 20; inter-rater reliability = 30; inter-device reliability = 25)



R = 0.90**; R^2** = 0.81**; Slope** = 0.85**; Intercept** = -12.12

Assessor-A knee extensors (Lafayette RFD):

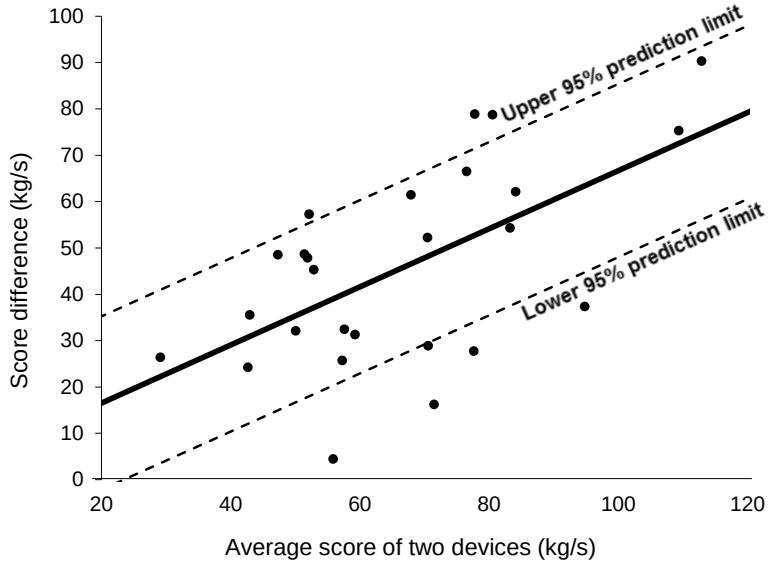
(n: validity = 25; Lafayette intra-rater reliability = 27; KinCom reliability = 20; inter-rater reliability = 28; inter-device reliability = 25)



R = 0.74**; R^2** = 0.55**; Slope** = 1.15**; Intercept** = -47.38

Assessor-A knee flexors (Lafayette RFD):

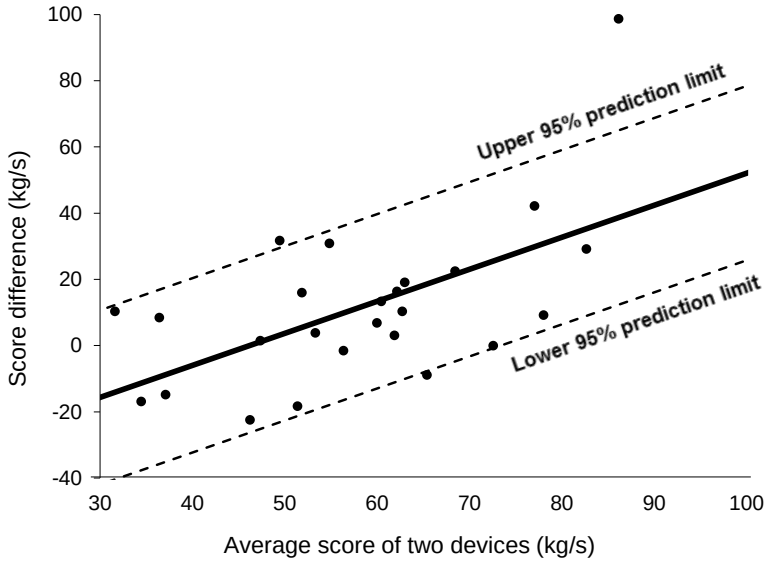
(n: validity = 26; Lafayette intra-rater reliability = 29; KinCom reliability = 20; inter-rater reliability = 30; inter-device reliability = 20)



R = 0.60**; R^2** = 0.35**; Slope** = 0.63**; Intercept** = 4.02

Assessor-B ankle dorsiflexors (Lafayette RFD):

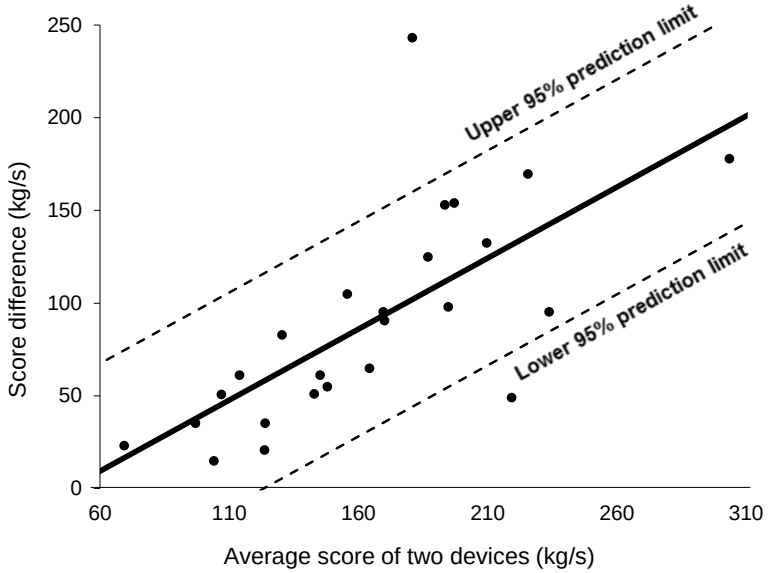
(n: validity = 25; Lafayette intra-rater reliability = 28; inter-device reliability = 27)



R = 0.58**; R^2** = 0.34**; Slope** = 0.97**; Intercept** = -44.62

Assessor-B ankle plantarflexors (Lafayette RFD):

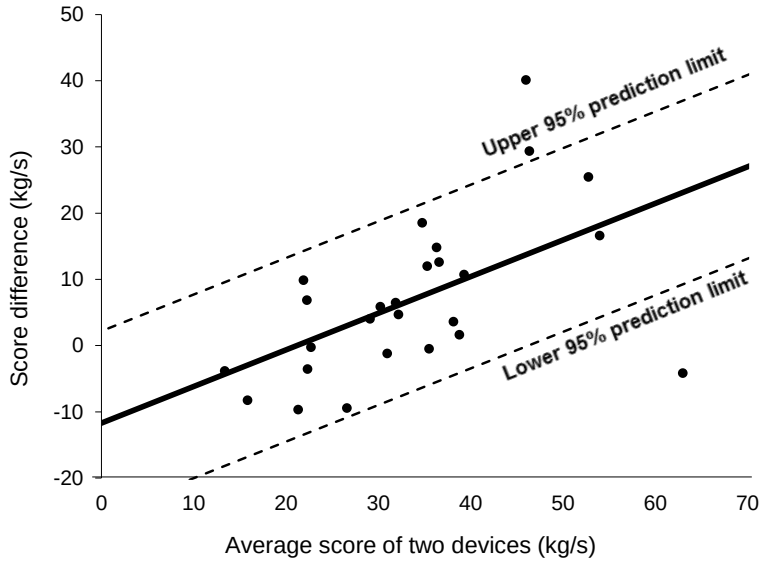
(n: validity = 25; Lafayette intra-rater reliability = 28; inter-device reliability = 27)



R = 0.70**; R^2** = 0.49**; Slope** = 0.77**; Intercept** = -36.42

Assessor-B hip abductors (Lafayette RFD):

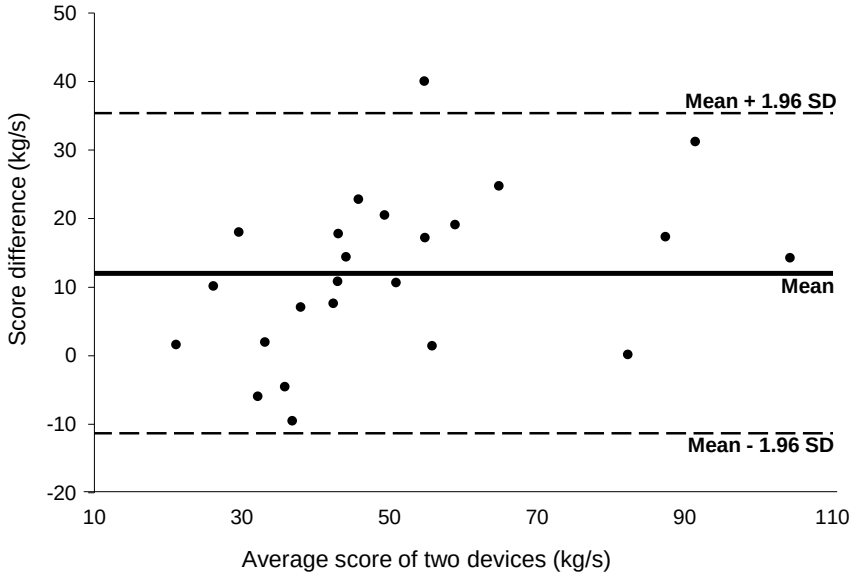
(n: validity = 26; Lafayette intra-rater reliability = 29; inter-device reliability = 29)



R = 0.54**; R^2** = 0.30**; Slope** = 0.55**; Intercept** = -11.69

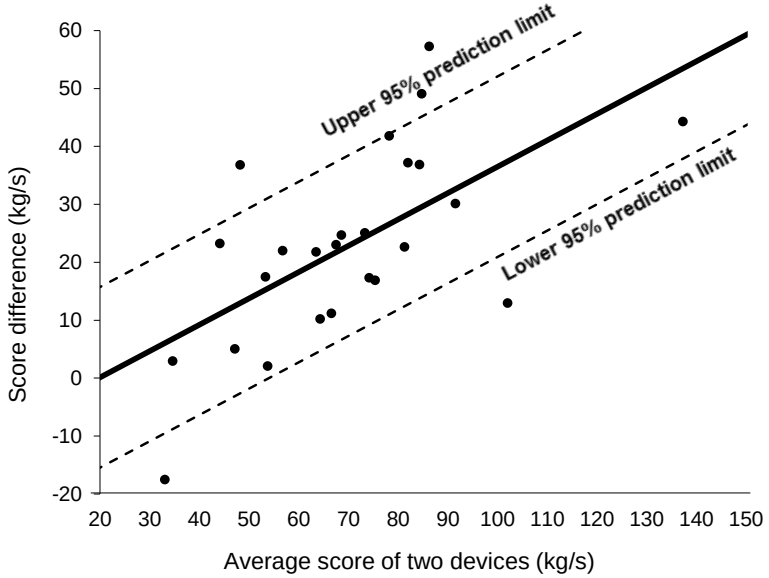
Assessor-B hip adductors (Lafayette RFD):

(n: validity = 24; Lafayette intra-rater reliability = 27; inter-device reliability = 26)



Assessor-B hip extensors (Lafayette RFD):

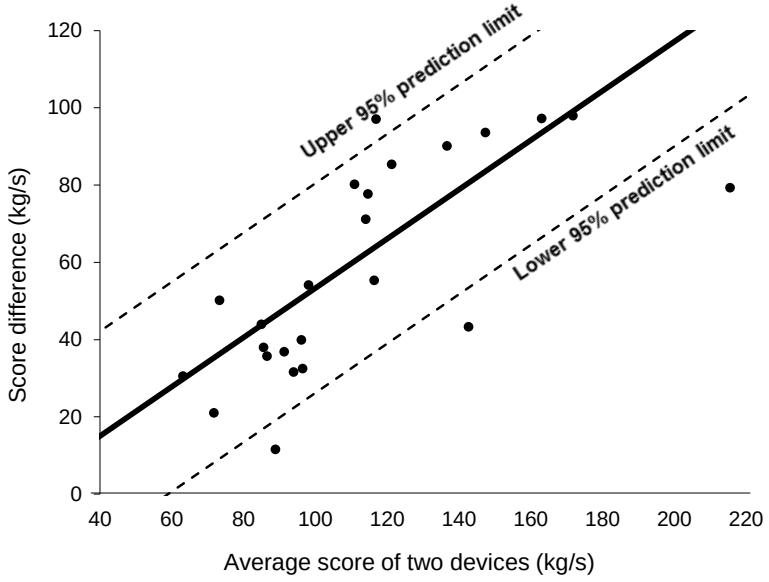
(n: validity = 25; Lafayette intra-rater reliability = 28; inter-device reliability = 27)



R = 0.62**; R^2** = 0.38**; Slope** = 0.45**; Intercept** = -8.95

Assessor-B hip flexors (Lafayette RFD):

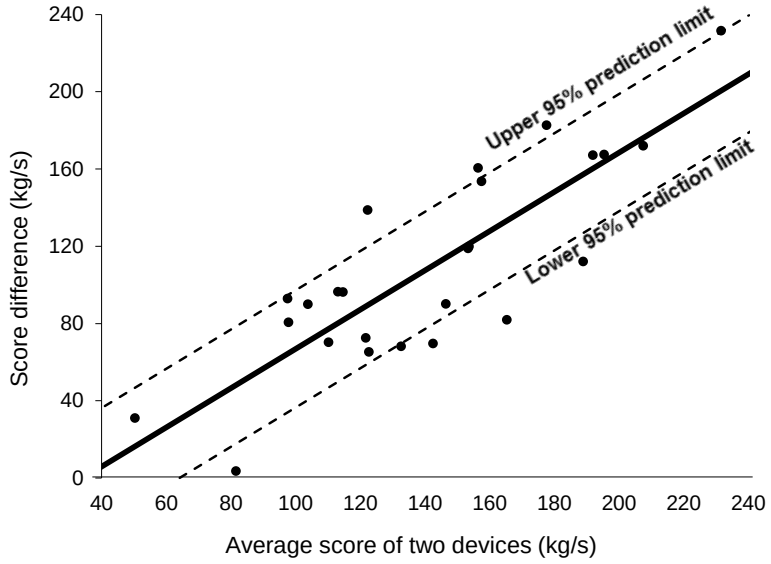
(n: validity = 26; Lafayette intra-rater reliability = 29; inter-device reliability = 27)



R = 0.72**; R^2** = 0.51**; Slope** = 0.64**; Intercept** = -10.45

Assessor-B knee extensors (Lafayette RFD):

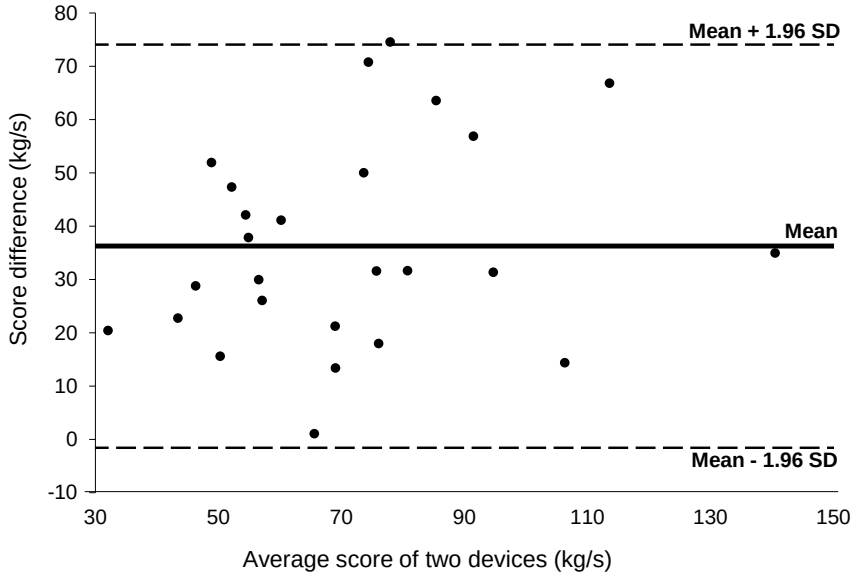
(n: validity = 25; Lafayette intra-rater reliability = 28; inter-device reliability = 28)



R = 0.83**; R^2** = 0.69**; Slope** = 1.02**; Intercept** = -34.58

Assessor-B knee flexors (Lafayette RFD):

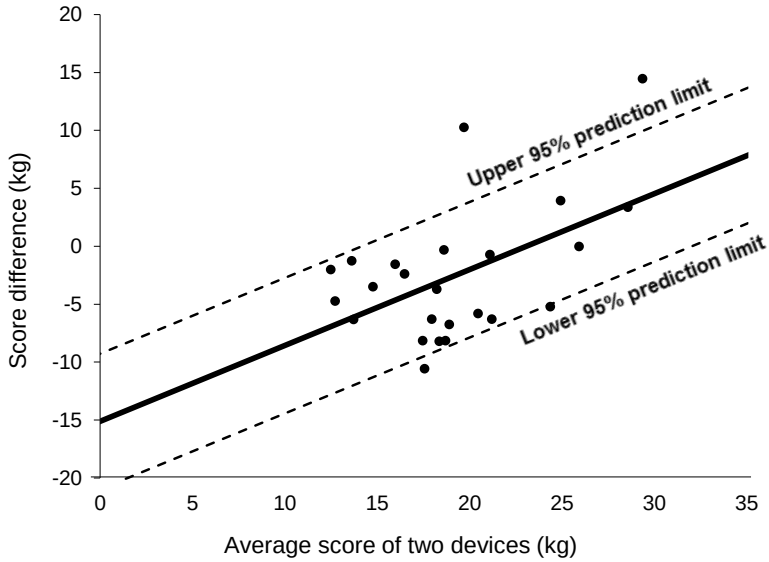
(n: validity = 26; Lafayette intra-rater reliability = 29; inter-device reliability = 24)



3. Hoggan Peak Force (kg)

Assessor-A ankle dorsiflexors (Hoggan peak force):

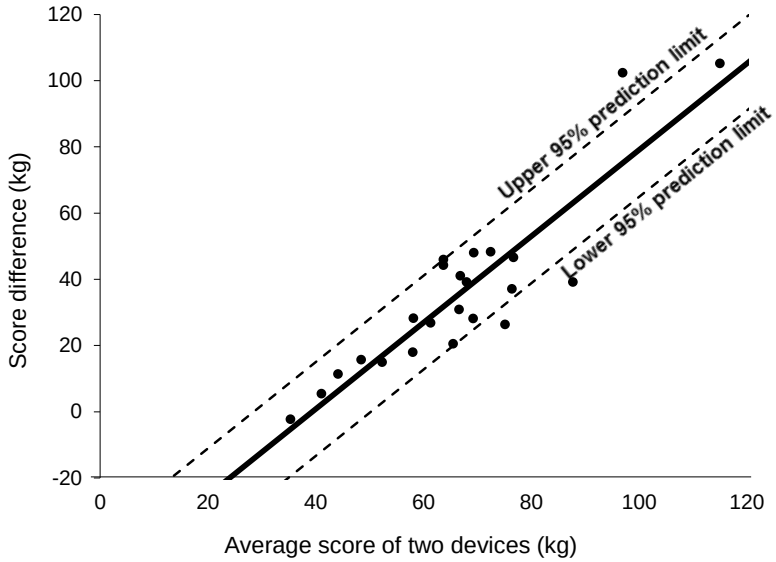
(n: validity = 24; Hoggan intra-rater reliability = 25; inter-rater reliability = 26)



R = 0.52**; R^2** = 0.27**; Slope** = 0.65**; Intercept** = -15.11

Assessor-A ankle plantarflexors (Hoggan peak force):

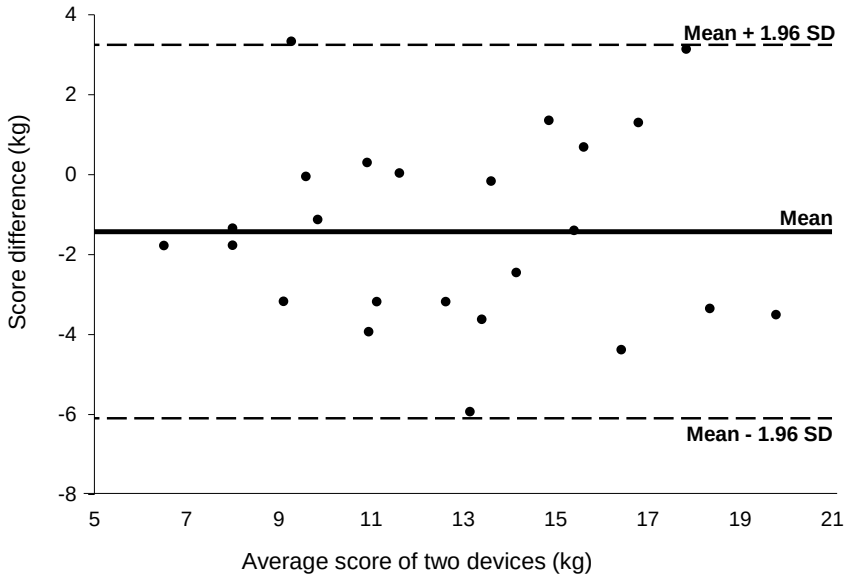
(n: validity = 23; Hoggan intra-rater reliability = 23; inter-rater reliability = 26)



R = 0.90**; R^2** = 0.81**; Slope** = 1.30**; Intercept** = -51.28

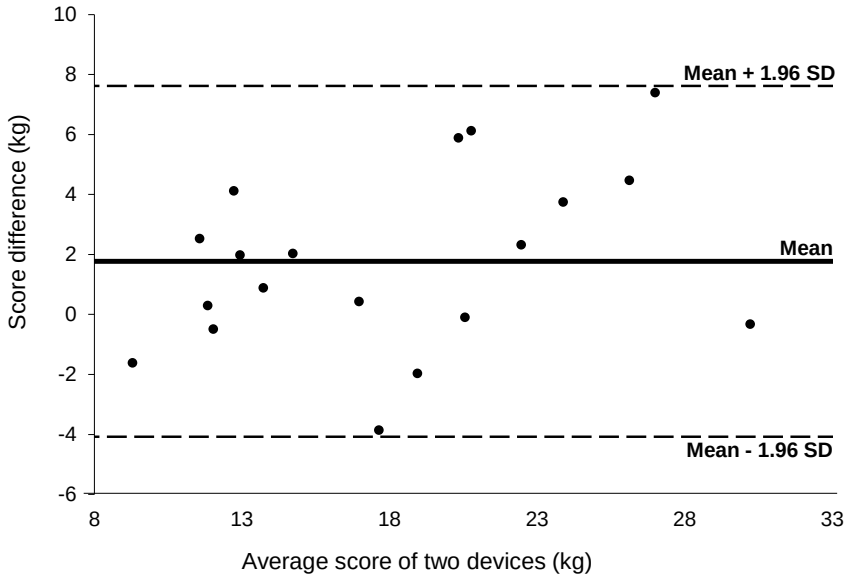
Assessor-A hip abductors (Hoggan peak force):

(n: validity = 24; Hoggan intra-rater reliability = 26; inter-rater reliability = 28)



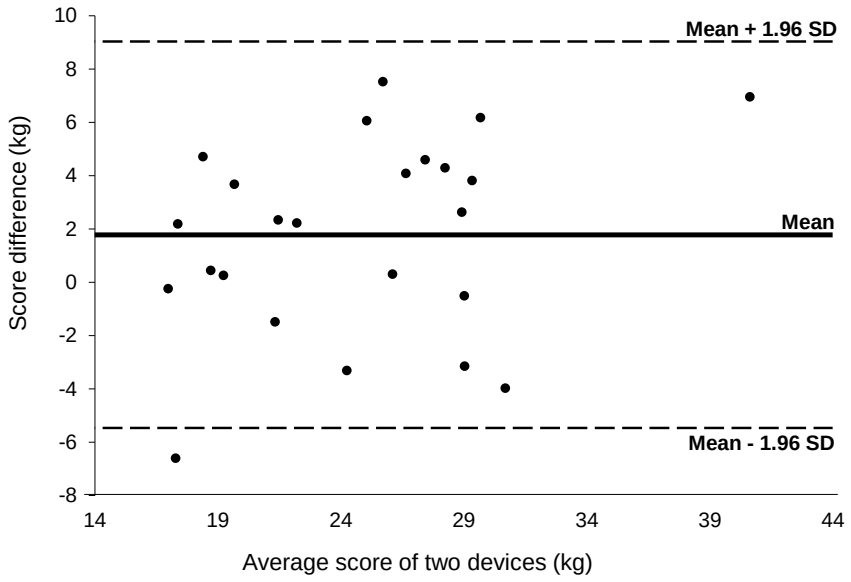
Assessor-A hip adductors (Hoggan peak force):

(n: validity = 19; Hoggan intra-rater reliability = 23; inter-rater reliability = 23)



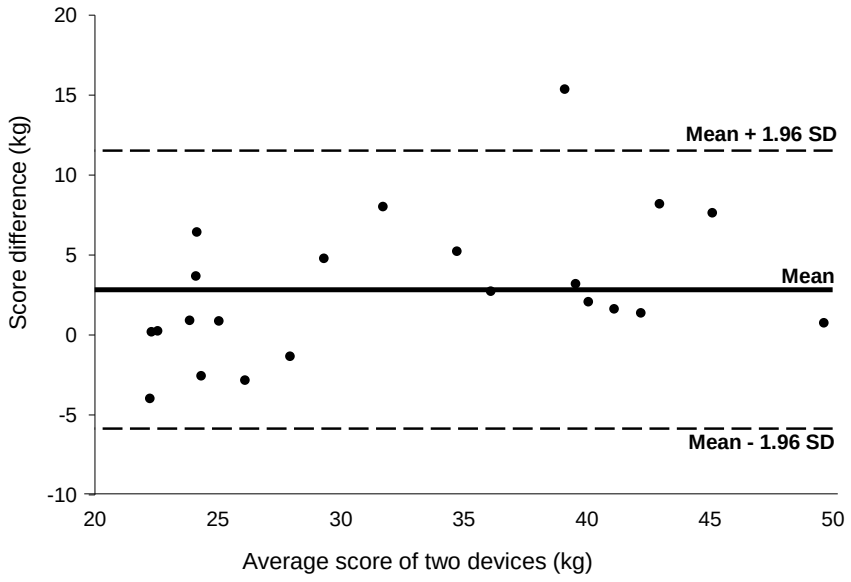
Assessor-A hip extensors (Hoggan peak force):

(n: validity = 24; Hoggan intra-rater reliability = 26; inter-rater reliability = 27)



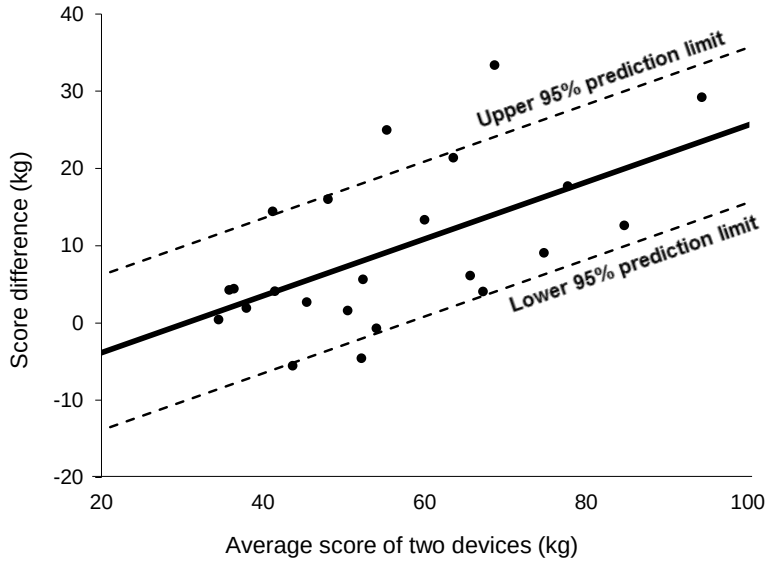
Assessor-A hip flexors (Hoggan peak force):

(n: validity = 22; Hoggan intra-rater reliability = 23; inter-rater reliability = 23)



Assessor-A knee extensors (Hoggan peak force):

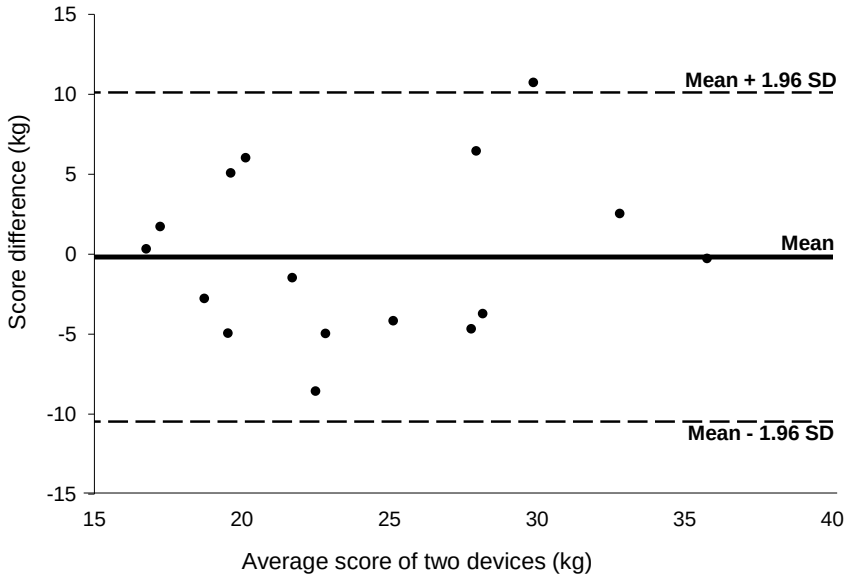
(n: validity = 23; Hoggan intra-rater reliability = 20; inter-rater reliability = 25)



R = 0.58**; R^2** = 0.34**; Slope** = 0.37**; Intercept** = -11.18

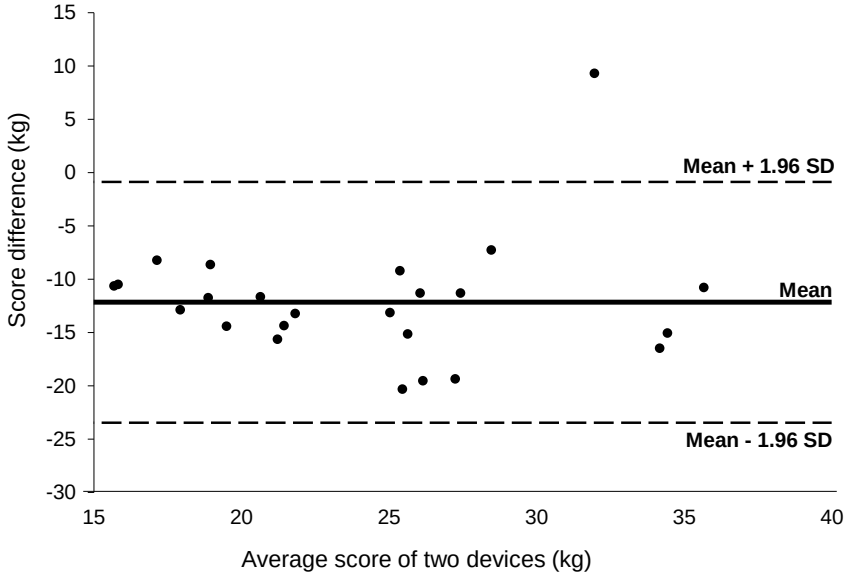
Assessor-A knee flexors (Hoggan peak force):

(n: validity = 16; Hoggan intra-rater reliability = 17; inter-rater reliability = 16)



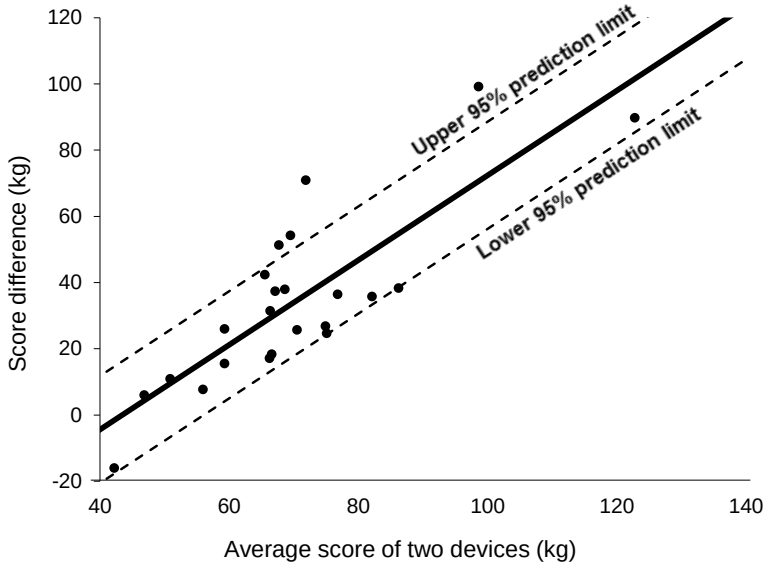
Assessor-B ankle dorsiflexors (Hoggan peak force):

(n: validity = 24; Hoggan intra-rater reliability = 27)



Assessor-B ankle plantarflexors (Hoggan peak force):

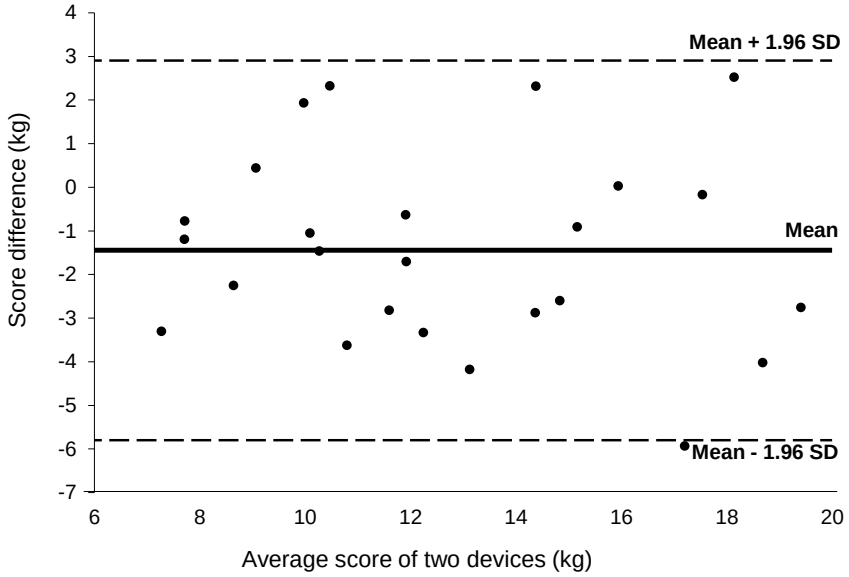
(n: validity = 23; Hoggan intra-rater reliability = 23)



R = 0.82**; R^2** = 0.68**; Slope** = 1.28**; Intercept** = -55.48

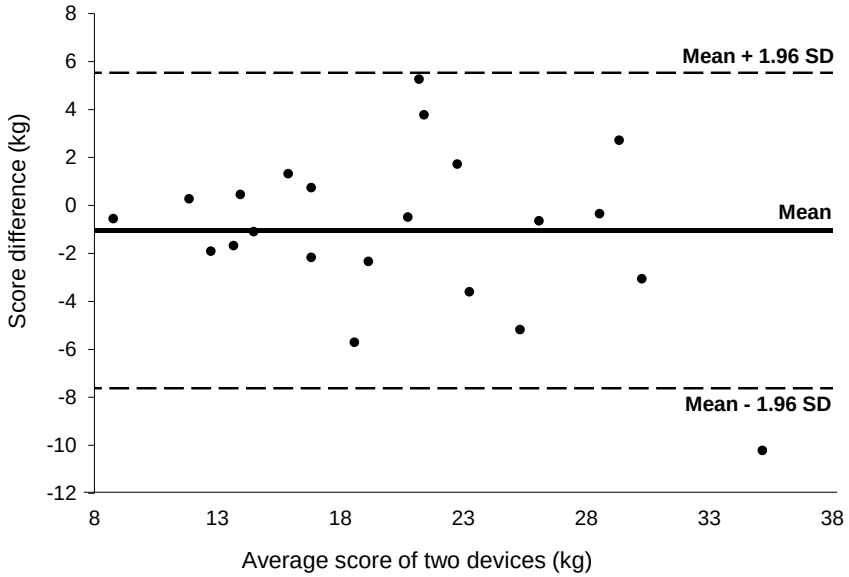
Assessor-B hip abductors (Hoggan peak force):

(n: validity = 25; Hoggan intra-rater reliability = 28)



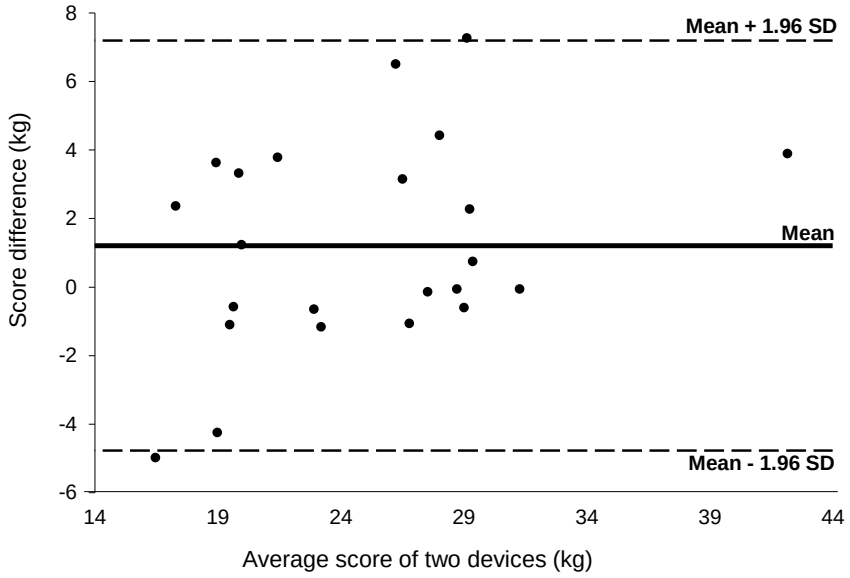
Assessor-B hip adductors (Hoggan peak force):

(n: validity = 22; Hoggan intra-rater reliability = 22)



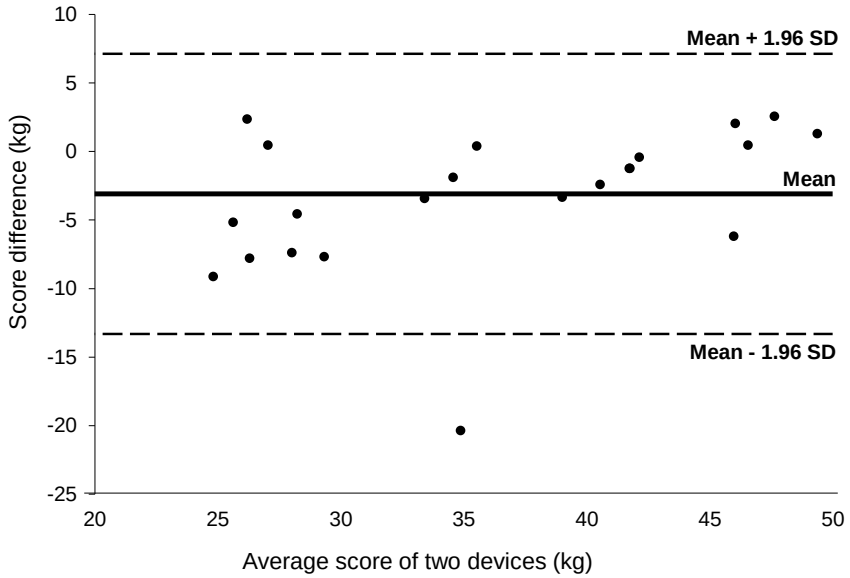
Assessor-B hip extensors (Hoggan peak force):

(n: validity = 23; Hoggan intra-rater reliability = 24)



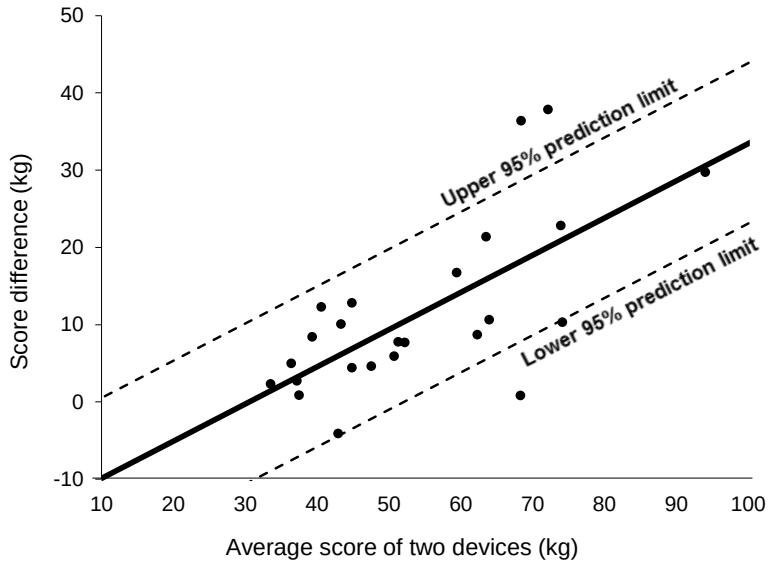
Assessor-B hip flexors (Hoggan peak force):

(n: validity = 23; Hoggan intra-rater reliability = 25)



Assessor-B knee extensors (Hoggan peak force):

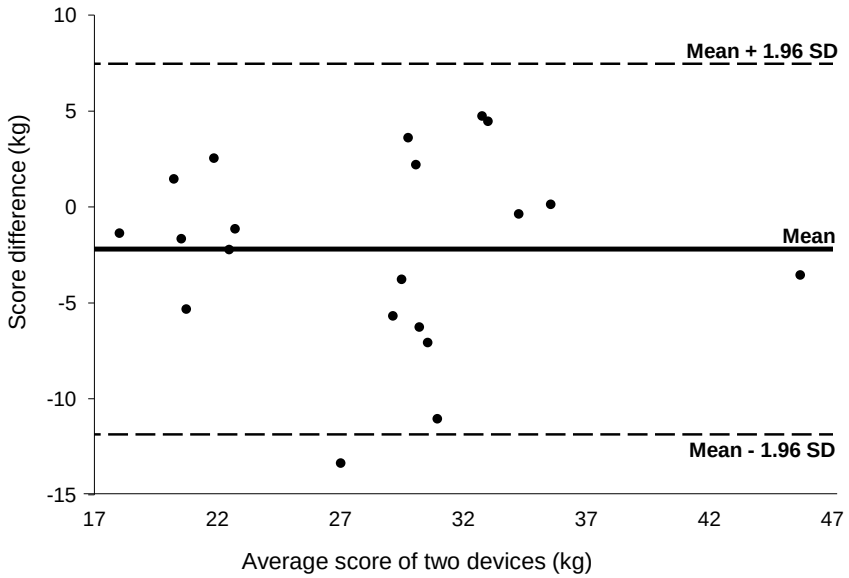
(n: validity = 24; Hoggan intra-rater reliability = 27)



R = 0.69**; R^2** = 0.47**; Slope** = 0.48**; Intercept** = -14.67

Assessor-B knee flexors (Hoggan peak force):

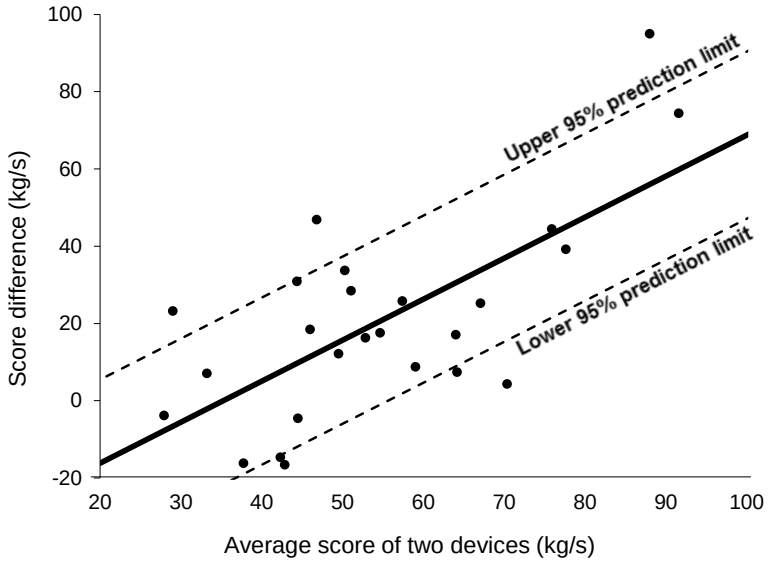
(n: validity = 20; Hoggan intra-rater reliability = 24)



4. Hoggan RFD (kg/s)

Assessor-A ankle dorsiflexors (Hoggan RFD):

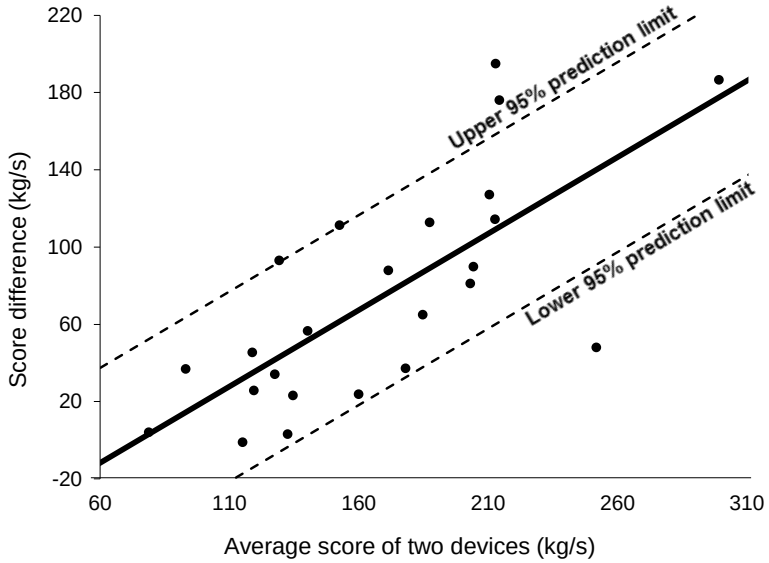
(n: validity = 25; Hoggan intra-rater reliability = 25; inter-rater reliability = 26)



R = 0.69**; R^2** = 0.47**; Slope** = 1.06**; Intercept** = -37.36

Assessor-A ankle plantarflexors (Hoggan RFD):

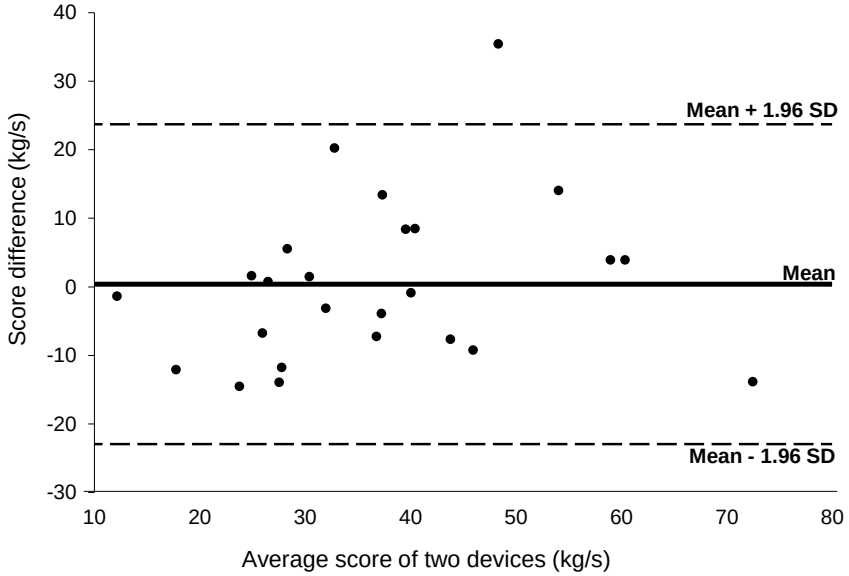
(n: validity = 24; Hoggan intra-rater reliability = 23; inter-rater reliability = 26)



R = 0.73**; R^2** = 0.53**; Slope** = 0.79**; Intercept** = -59.08

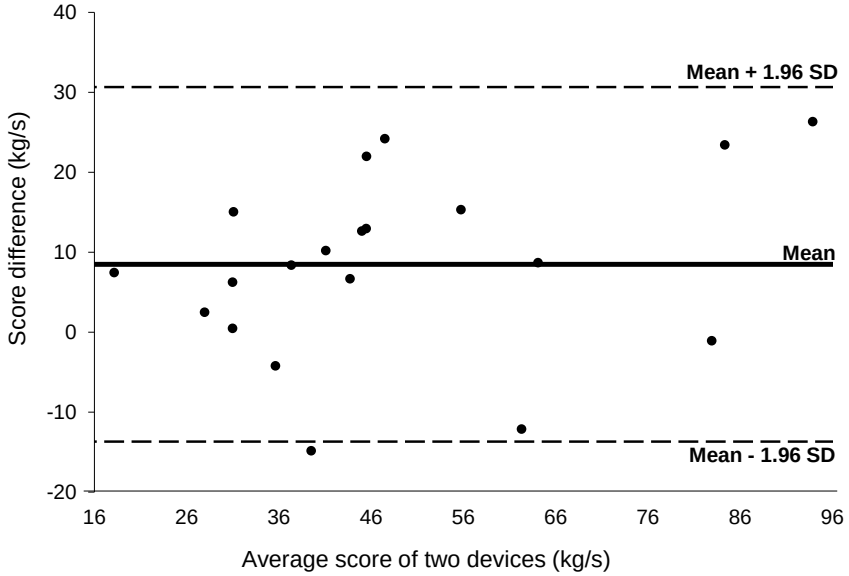
Assessor-A hip abductors (Hoggan RFD):

(n: validity = 25; Hoggan intra-rater reliability = 26; inter-rater reliability = 28)



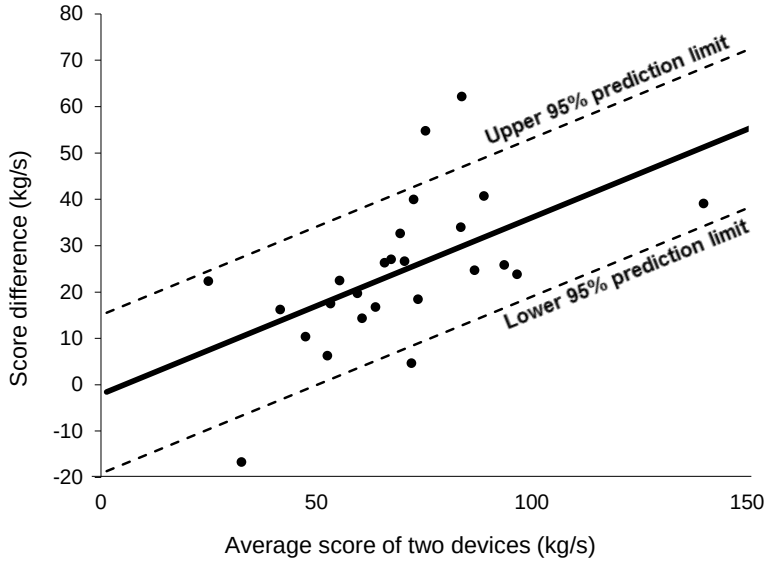
Assessor-A hip adductors (Hoggan RFD):

(n: validity = 20; Hoggan intra-rater reliability = 18; inter-rater reliability = 23)



Assessor-A hip extensors (Hoggan RFD):

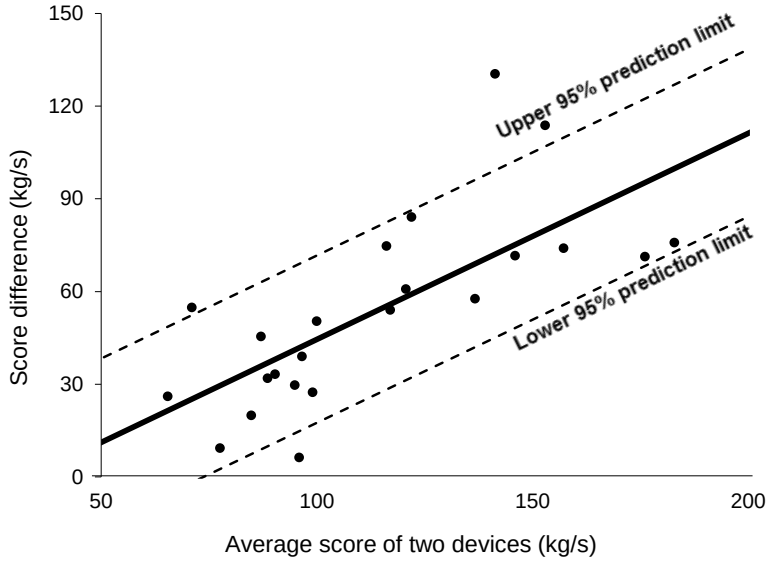
(n: validity = 25; Hoggan intra-rater reliability = 26; inter-rater reliability = 27)



R = 0.55**; R^2** = 0.30**; Slope** = 0.38**; Intercept** = -2.06

Assessor-A hip flexors (Hoggan RFD):

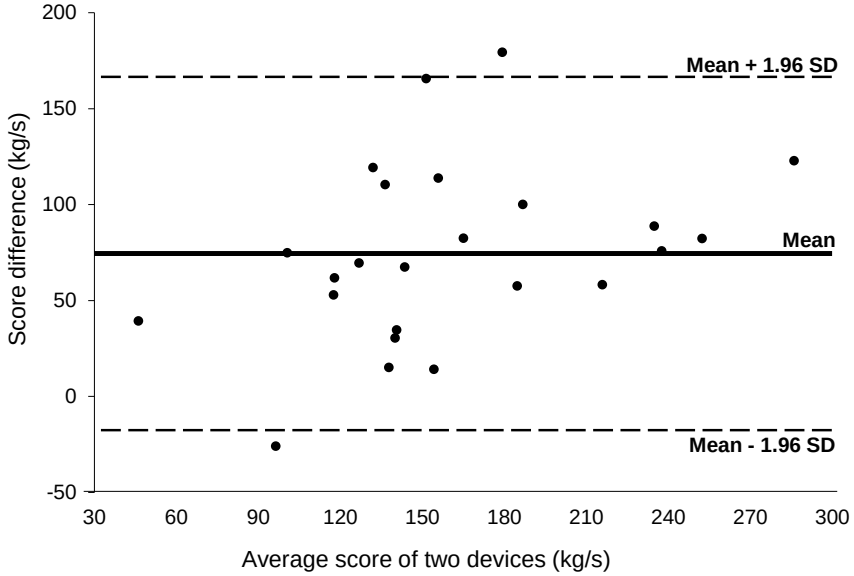
(n: validity = 23; Hoggan intra-rater reliability = 23; inter-rater reliability = 23)



R = 0.71**; R^2** = 0.51**; Slope** = 0.67**; Intercept** = -22.08

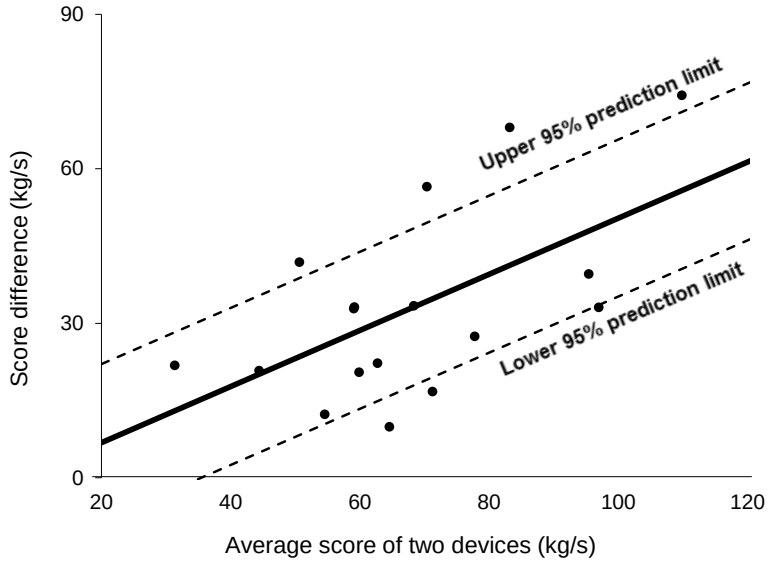
Assessor-A knee extensors (Hoggan RFD):

(n: validity = 24; Hoggan intra-rater reliability = 20; inter-rater reliability = 25)



Assessor-A knee flexors (Hoggan RFD):

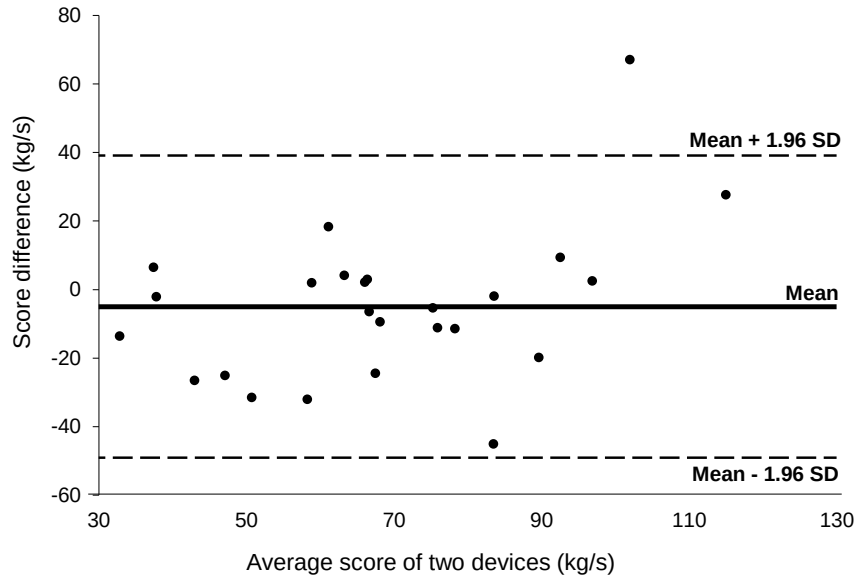
(n: validity = 17; Hoggan intra-rater reliability = 17; inter-rater reliability = 16)



R = 0.59**; R^2** = 0.35**; Slope** = 0.54**; Intercept** = -4.03

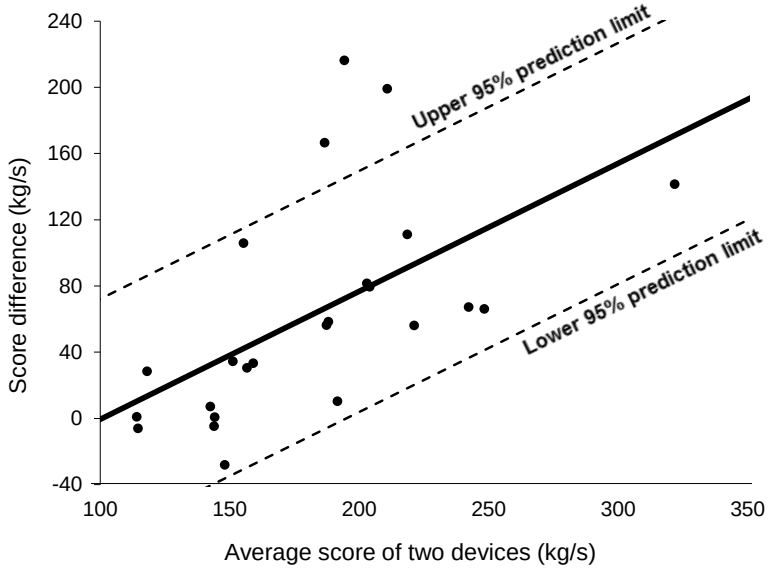
Assessor-B ankle dorsiflexors (Hoggan RFD):

(n: validity = 25; Hoggan intra-rater reliability = 27)



Assessor-B ankle plantarflexors (Hoggan RFD):

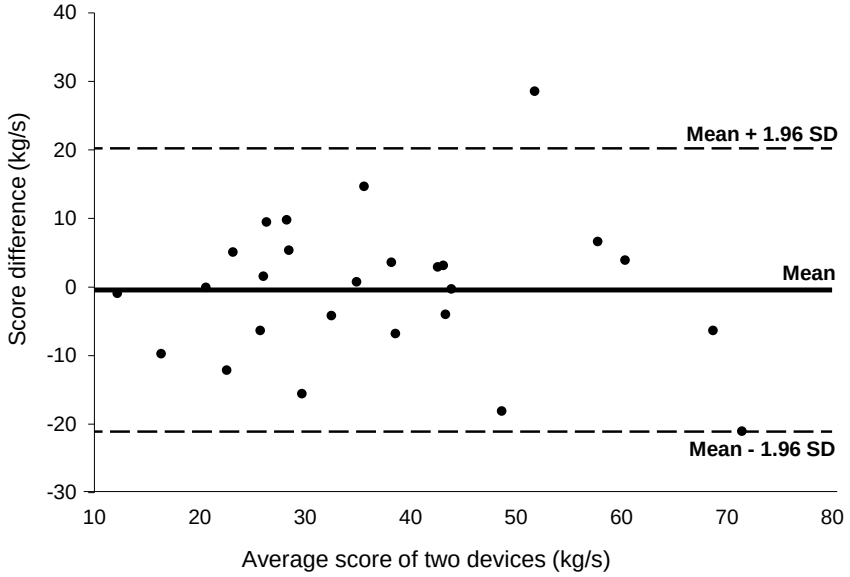
(n: validity = 24; Hoggan intra-rater reliability = 23)



R = 0.57**; R^2** = 0.33**; Slope** = 0.77**; Intercept** = -77.81

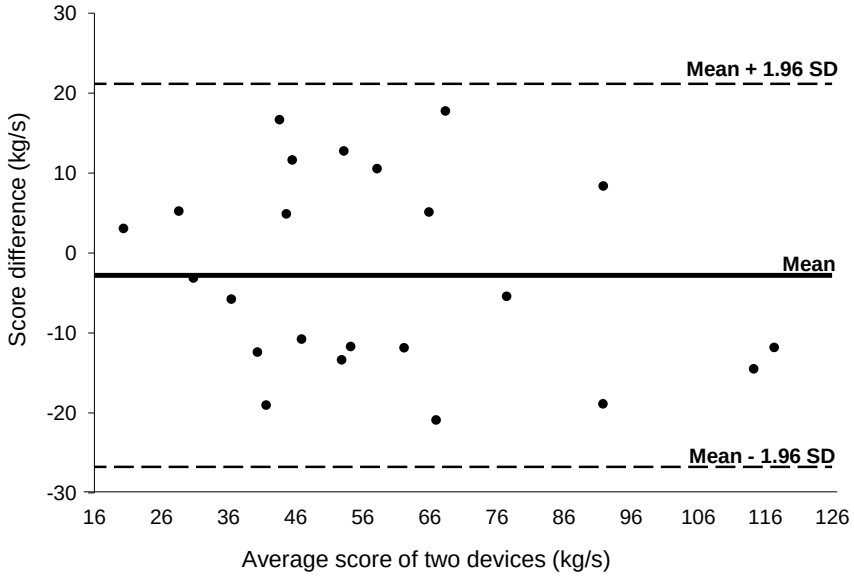
Assessor-B hip abductors (Hoggan RFD):

(n: validity = 26; Hoggan intra-rater reliability = 28)



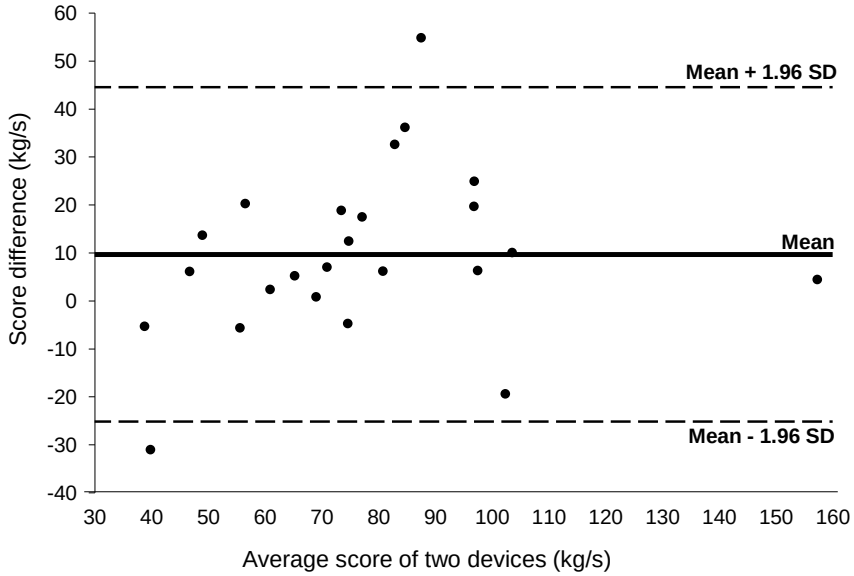
Assessor-B hip adductors (Hoggan RFD):

(n: validity = 23; Hoggan intra-rater reliability = 22)



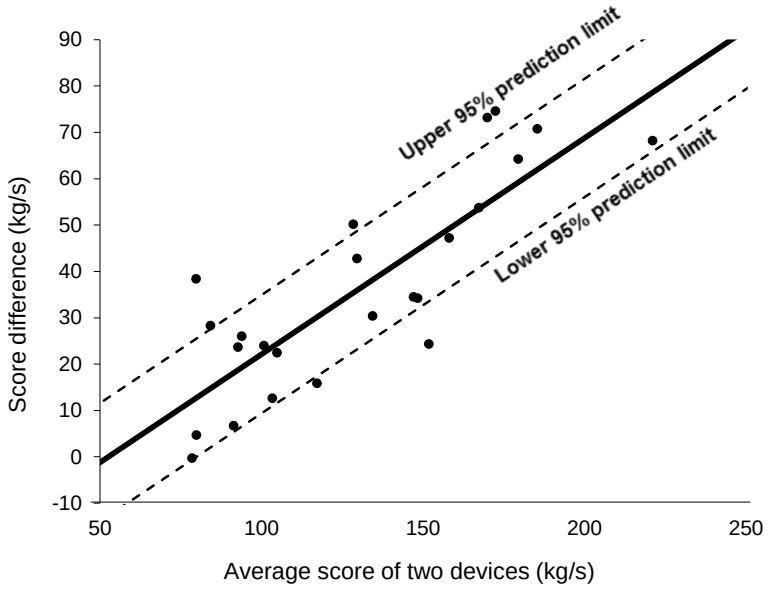
Assessor-B hip extensors (Hoggan RFD):

(n: validity = 24; Hoggan intra-rater reliability = 24)



Assessor-B hip flexors (Hoggan RFD):

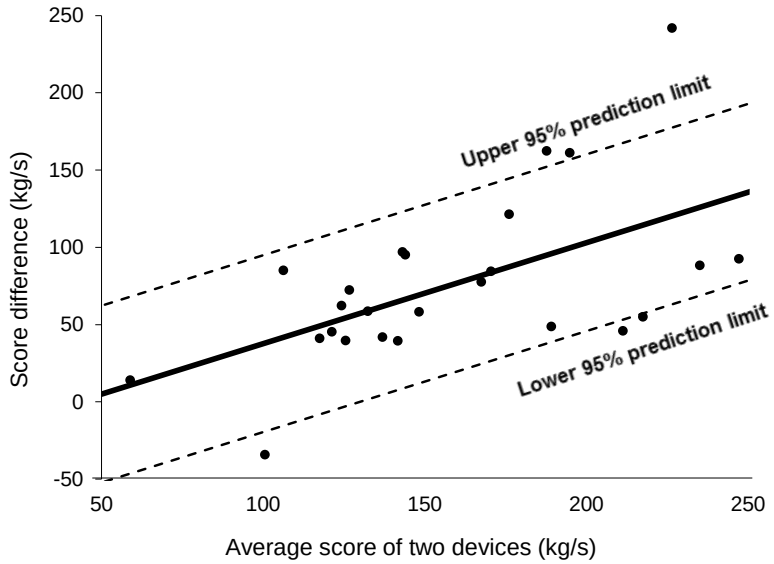
(n: validity = 24; Hoggan intra-rater reliability = 25)



R = 0.83**; R^2** = 0.70**; Slope** = 0.47**; Intercept** = -24.44

Assessor-B knee extensors (Hoggan RFD):

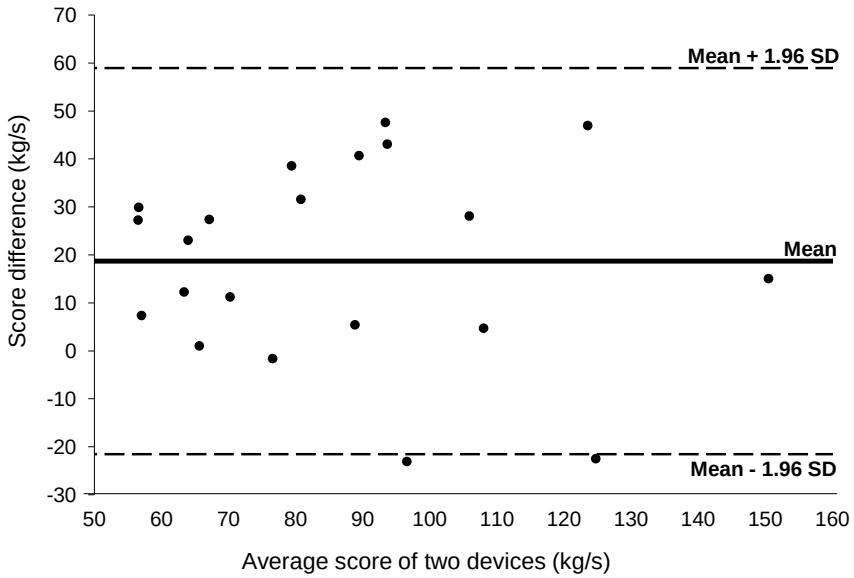
(n: validity = 25; Hoggan intra-rater reliability = 27)



R = 0.56**; R^2** = 0.32**; Slope** = 0.65**; Intercept** = -27.60

Assessor-B knee flexors (Hoggan RFD):

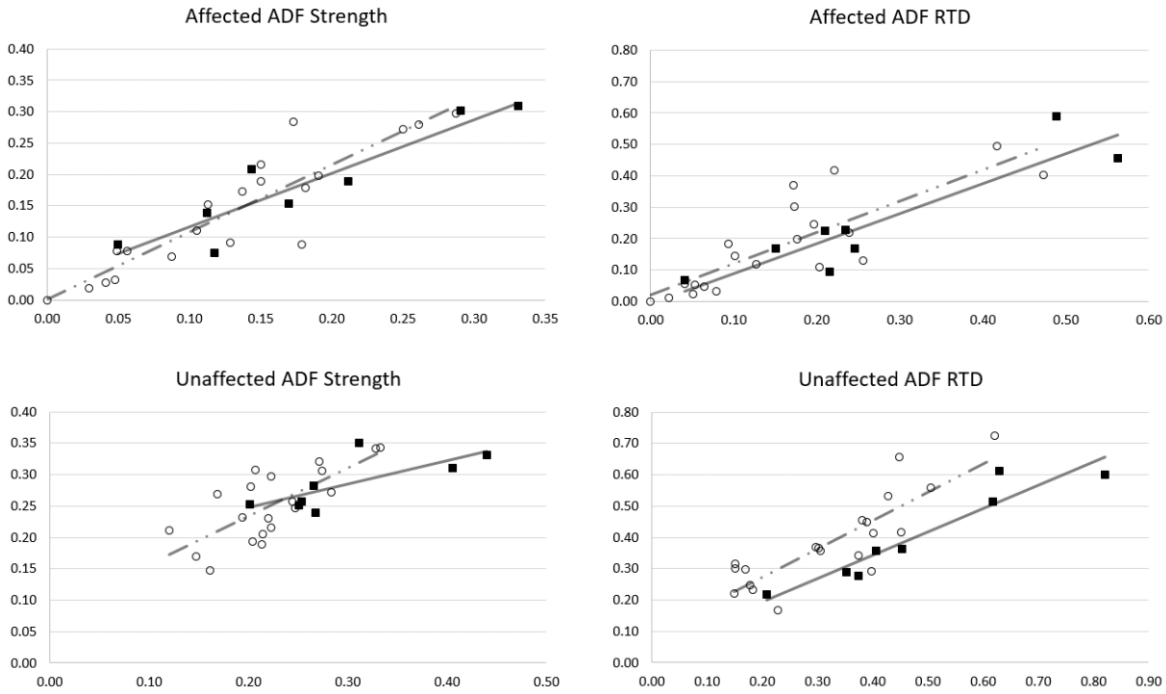
(n: validity = 21; Hoggan intra-rater reliability = 19)

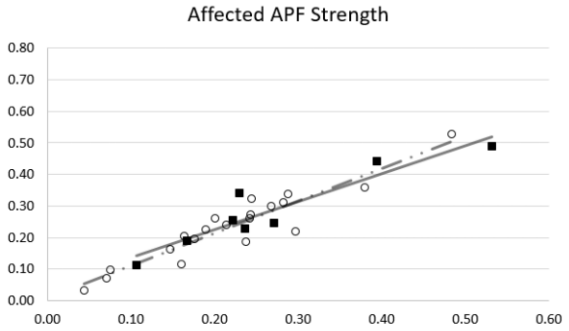


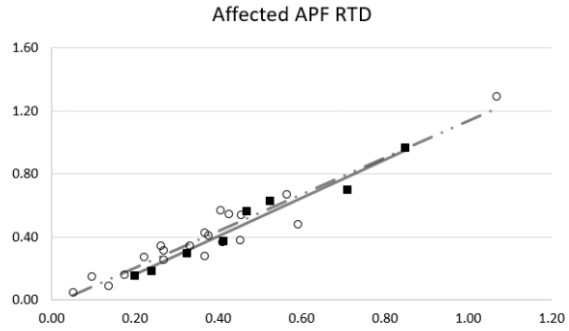
Appendix C – Extra results from Study Three

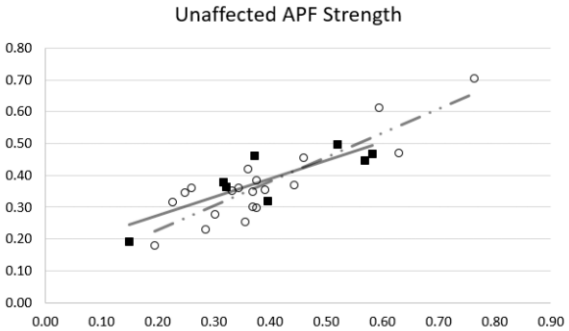
Scatter plots comparing the test-retest reliability for hand-held dynamometry to measure isometric strength and rate of torque development comparing participants who returned ≤ 14 days and those who returned > 14 days later.

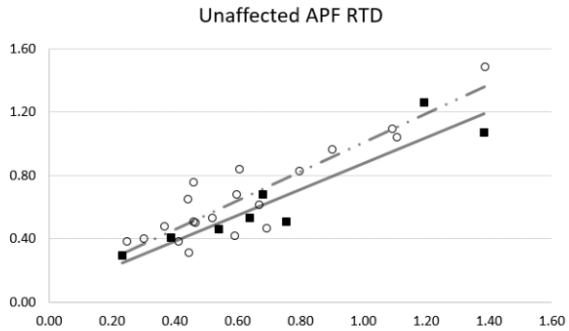
The circle points are those who returned ≤ 14 days later (dashed linear trend line) and the square points are those who returned > 14 days later (solid linear trend line). Data shown for both the paretic (affected) and non-paretic (unaffected) side (session 1 on the x-axis and session 2 on the y-axis). Units for the strength graphs is Nm/kg and the units for the rate of torque development graphs is Nm/s/kg. There is no trend in the data to suggest any differences in reliability between the two groups.

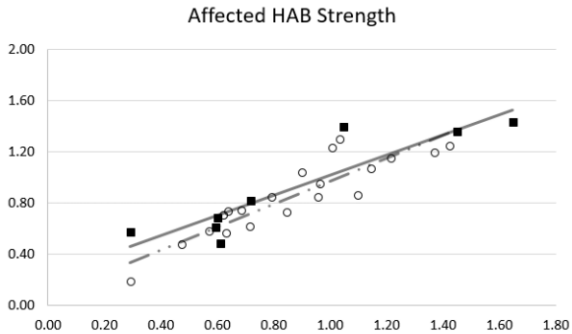


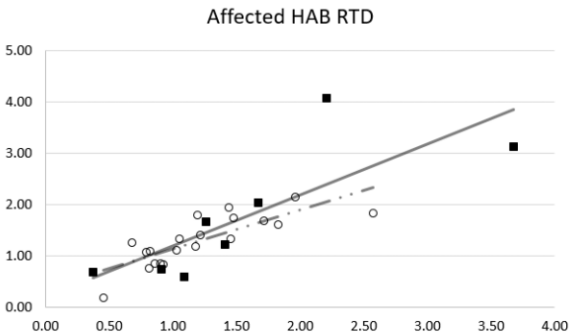

Affected APF Strength
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00 0.10 0.20 0.30 0.40 0.50 0.60

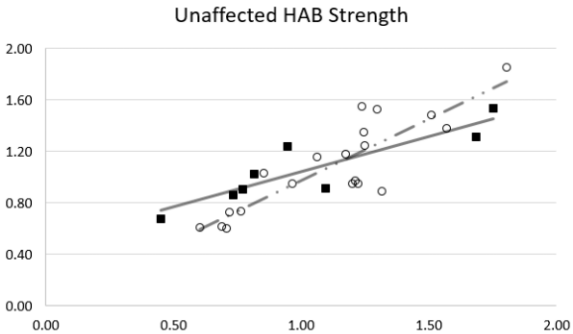

Affected APF RTD
1.60
1.20
0.80
0.40
0.00
0.00 0.20 0.40 0.60 0.80 1.00 1.20

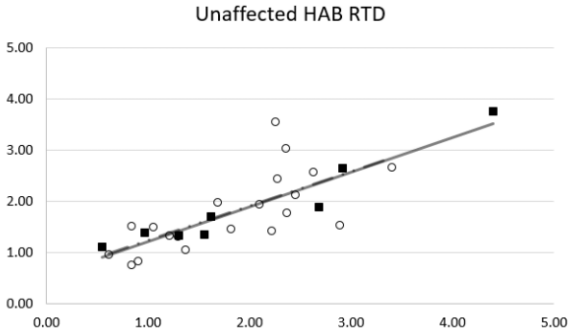

Unaffected APF Strength
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90

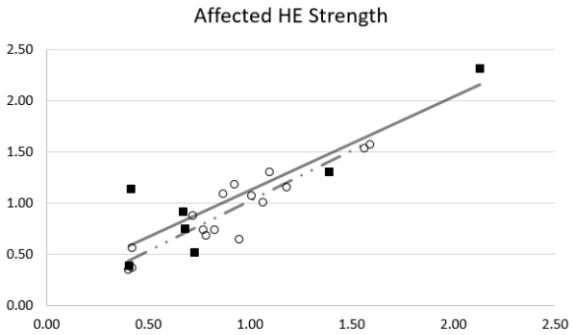

Unaffected APF RTD
1.60
1.20
0.80
0.40
0.00
0.00 0.20 0.40 0.60 0.80 1.00 1.20 1.40 1.60

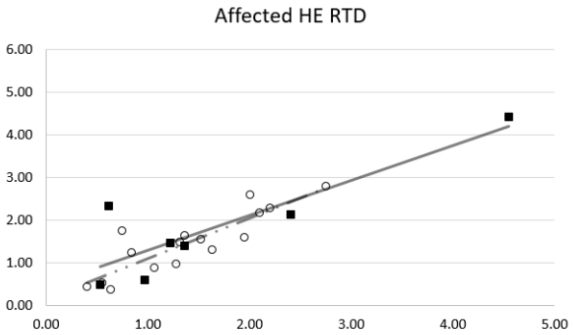

Affected HAB Strength
2.00
1.60
1.20
0.80
0.40
0.00
0.00 0.20 0.40 0.60 0.80 1.00 1.20 1.40 1.60 1.80

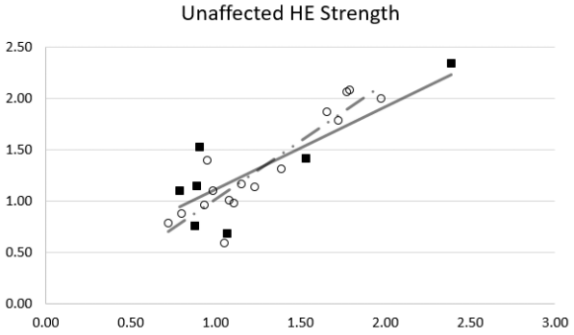

Affected HAB RTD
5.00
4.00
3.00
2.00
1.00
0.00
0.00 0.50 1.00 1.50 2.00 2.50 3.00 3.50 4.00

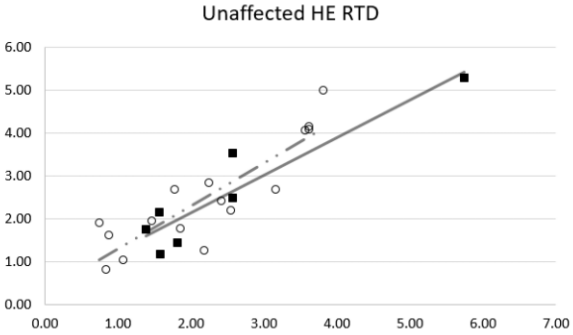

Unaffected HAB Strength
2.00
1.60
1.20
0.80
0.40
0.00
0.00 0.50 1.00 1.50 2.00


Unaffected HAB RTD
5.00
4.00
3.00
2.00
1.00
0.00
0.00 1.00 2.00 3.00 4.00 5.00


Affected HE Strength
2.50
2.00
1.50
1.00
0.50
0.00
0.00 0.50 1.00 1.50 2.00 2.50


Affected HE RTD
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.00 1.00 2.00 3.00 4.00 5.00


Unaffected HE Strength
2.50
2.00
1.50
1.00
0.50
0.00
0.00 0.50 1.00 1.50 2.00 2.50 3.00


Unaffected HE RTD
6.00
5.00
4.00
3.00
2.00
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0.00
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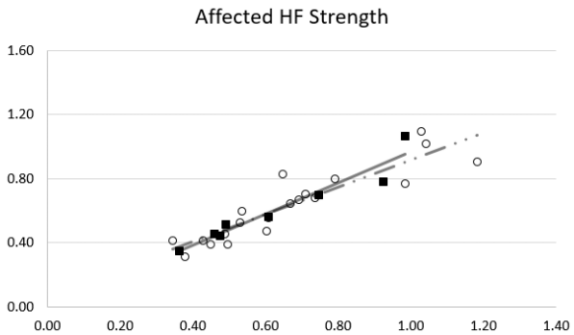
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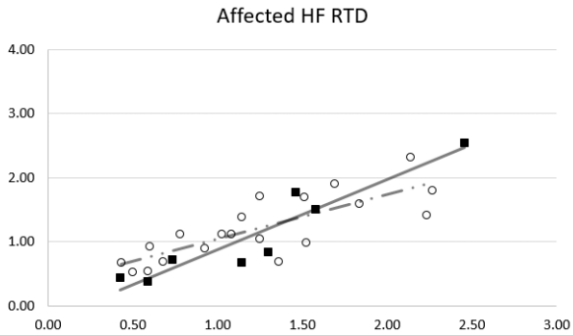
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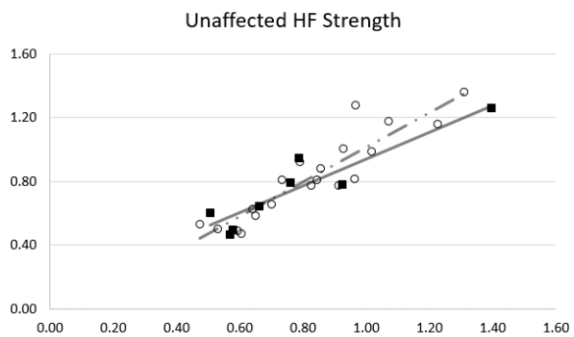
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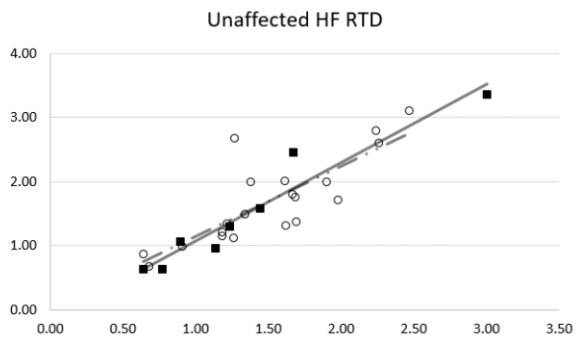
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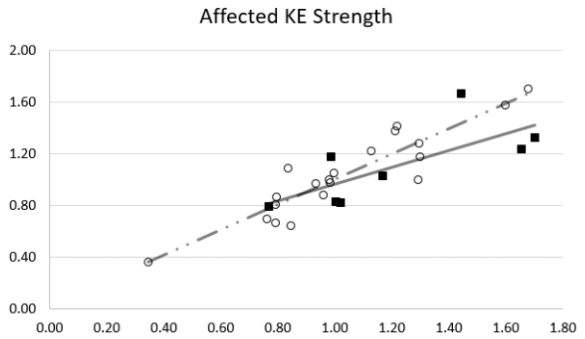
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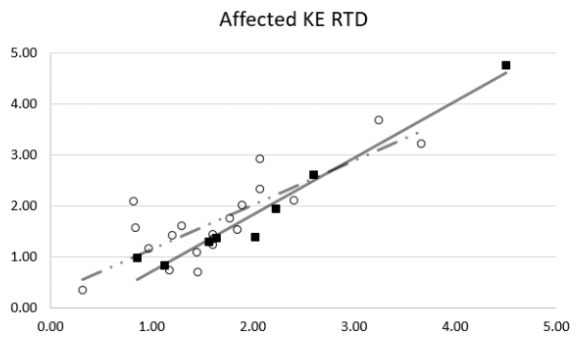
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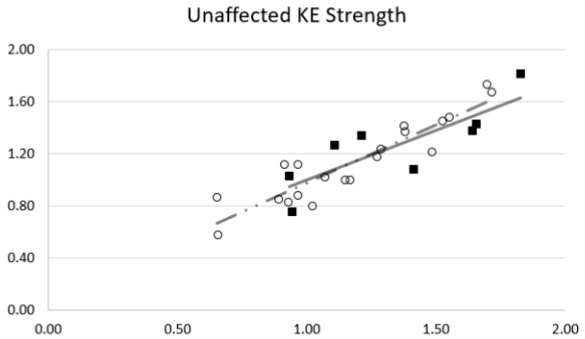
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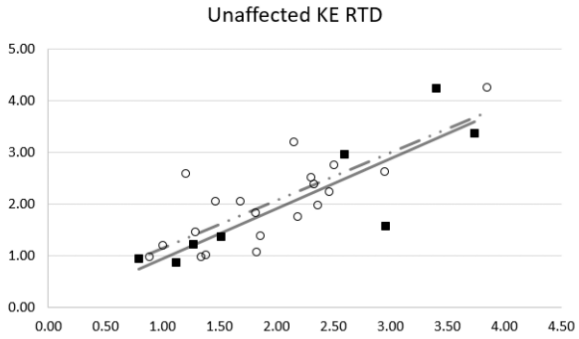
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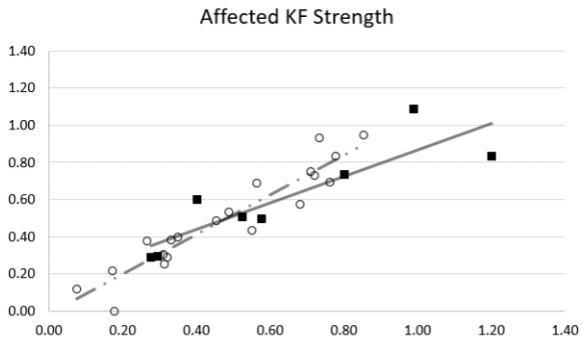
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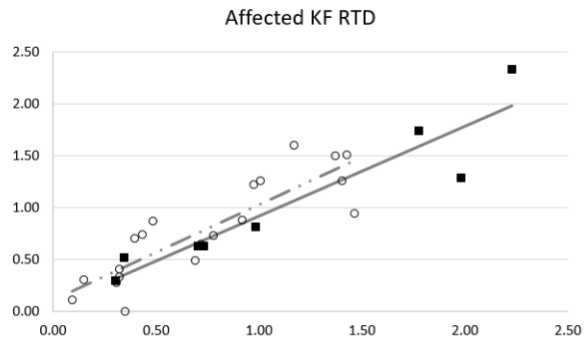
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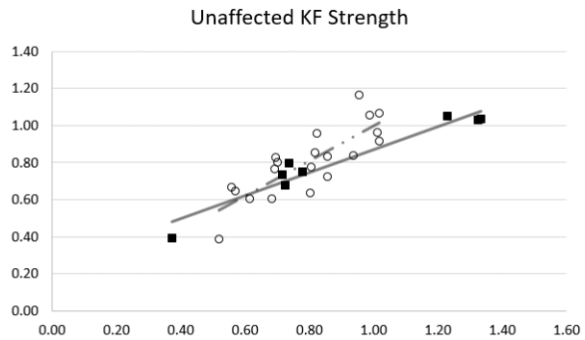
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0.20
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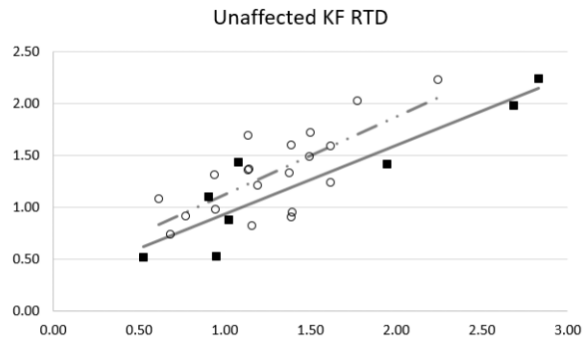
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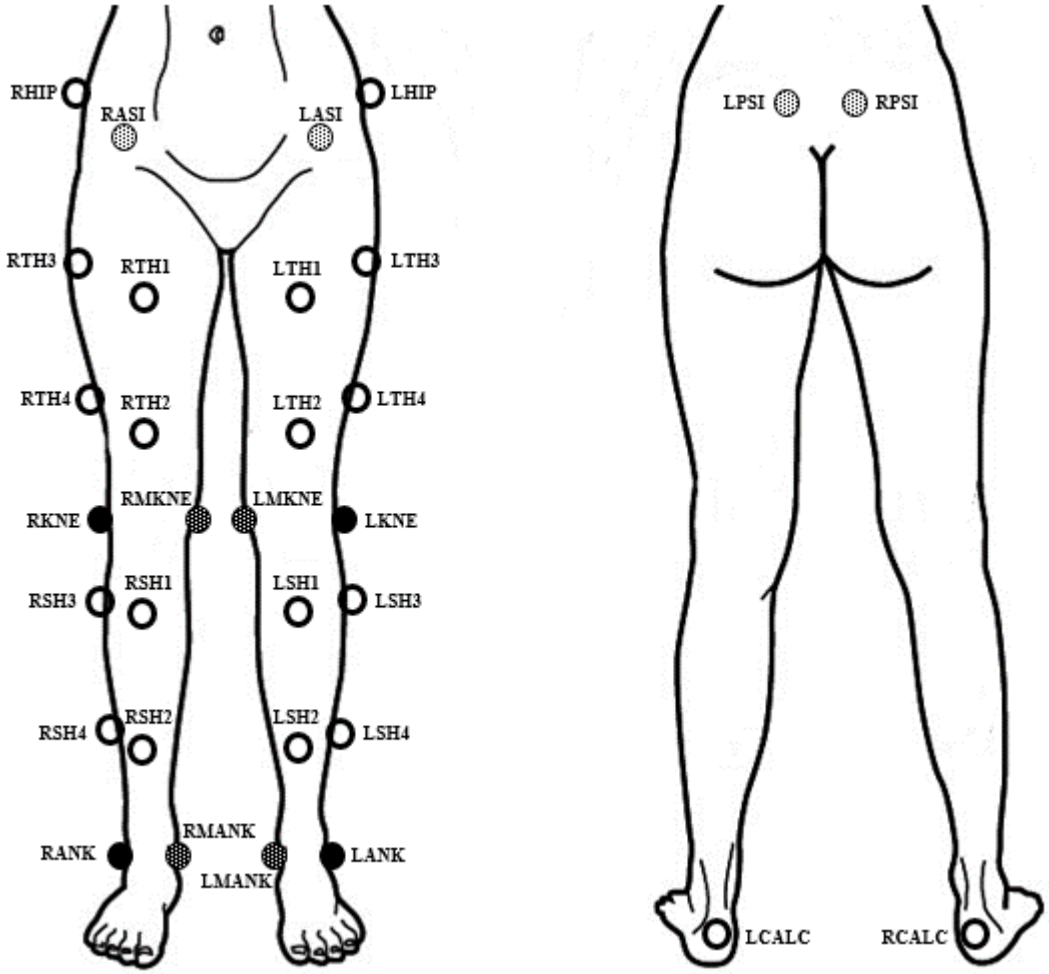
Appendix D – Lower limb gait model used for Study Four



Marker placement of the gait model for three-dimensional gait analysis. Solid markers = used for joint centre definition; hollow markers = used as tracking markers; black with white dot markers = used for joint centre definition and removed during walking trials; white with black dot markers = used for joint centre definition and as tracking markers.

Appendix Table 2. Anatomical marker locations

Marker ID	Marker name	Anatomical position
Pelvis		
LASI/RASI	Anterior superior iliac spine	Placed on the anterior superior iliac spine
LPSI/RPSI	Posterior superior iliac spine	Placed on the posterior superior iliac spine
LHIP/RHIP	Lateral iliac crest	Placed on the most lateral aspect of the iliac crest
Thigh		
LTH1/RTH1	Proximal anterior thigh	Placed on the proximal and anterior aspect of the thigh
LTH2/RTH2	Distal anterior thigh	Placed on the distal and anterior aspect of the thigh
LTH3/RTH3	Proximal lateral thigh	Placed on the proximal and lateral aspect of the thigh
LTH4/RTH4	Distal lateral thigh	Placed on the distal and lateral aspect of the thigh
LKNE/RKNE	Lateral knee joint	Placed on the lateral epicondyle of the knee
LMKNE/RMKNE	Medial knee joint	Placed on the medial epicondyle of the knee
Shank		
LSH1/RSH1	Proximal anterior shank	Placed on the proximal and anterior aspect of the shank
LSH2/RSH2	Distal anterior shank	Placed on the distal and anterior aspect of the shank
LSH3/RSH3	Proximal lateral shank	Placed on the proximal and lateral aspect of the shank
LSH4/RSH4	Distal lateral shank	Placed on the distal and lateral aspect of the shank
LANK/RANK	Lateral ankle joint	Placed on the lateral prominence of the lateral malleolus
LMANK/RMANK	Medial ankle joint	Placed on the medial prominence of the medial malleolus
Foot		
LCALC/RCALC	Calcaneus	Placed on the calcaneus distal to the Achilles tendon
LMT1/RMT1	Head of 1st metatarsal	Placed on the head of the first metatarsal
LMT23*/RMT23*	Head of 2nd/3rd metatarsal	Placed between the head of the second and third metatarsal
LMT23a#/RMT23a#	Base of 2nd/3rd metatarsal	Placed between the base of the second and third metatarsal
LMT5/RMT5	Head of 5th metatarsal	Placed on the head of the fifth metatarsal
LNAV*/RNAV*	Navicular	Placed on the most prominent aspect of the navicular bone
LHMT5*/RHMT5*	Base of 5th metatarsal	Placed on the lateral aspect of the fifth metatarsal base

Note: * = marker only used at Australian site; # = marker only used at Singaporean site.

Appendix E – Statement of contribution of others

Study One

Mentiplay, B. F., Adair, B., Bower, K. J., Williams, G., Tole, G., & Clark, R. A. (2015). Associations between lower limb strength and gait velocity following stroke: A systematic review. *Brain Injury*, *29*(4), 409-422. doi: 10.3109/02699052.2014.995231

Intellectual input: Conceptual and methodological design: BFM, BA, KJB, GW, and RAC. Conducting the systematic search: BFM, and BA. Data Extraction: BFM, BA, and GT. Drafting the manuscript: BFM. Editing the manuscript, responding to reviewer feedback and approval of final draft: BFM, BA, KJB, GW, GT, and RAC.

I acknowledge that my contribution to the above paper is 60%.

09/12/2016

Benjamin Frydlender Mentiplay Date

I acknowledge that my contribution to the above paper is 10%.

09/12/2016

Brooke Adair Date

I acknowledge that my contribution to the above paper is 5%.

09/12/2016

Kelly J Bower Date

I acknowledge that my contribution to the above paper is 5%.

09/12/2016

Gavin Williams Date

I acknowledge that my contribution to the above paper is 10%.

09/12/2016

Genevieve Hendrey (Tole) Date

I acknowledge that my contribution to the above paper is 10%.

09/12/2016

Ross A Clark Date

Study Two

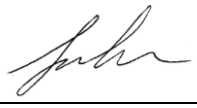
Mentiplay, B. F., Perraton, L. G., Bower, K. J., Adair, B., Pua, Y. H., Williams, G. P., McGaw, R., & Clark, R. A. (2015). Assessment of lower limb muscle strength and power using hand-held and fixed dynamometry: A reliability and validity study. *PLOS ONE, 10*(10), e0140822. doi: 10.1371/journal.pone.0140822

Intellectual input: Conceptual and methodological design: BFM, KJB, BA, YHP, GPW, and RAC. Gaining ethical approval: BFM, and RAC. Data collection: BFM, LGP, and RM. Data analysis: BFM, KJB, YHP, RM, and RAC. Drafting the manuscript: BFM. Editing the manuscript, responding to reviewer feedback and approval of the final draft: BFM, LGP, KJB, BA, YHP, GPW, RM, and RAC.

I acknowledge that my contribution to the above paper is 55%.

Benjamin Frydlender Mentiplay — 09/12/2016 Date

I acknowledge that my contribution to the above paper is 10%.



Luke G Perraton — 09/12/2016 Date

I acknowledge that my contribution to the above paper is 5%.

Kelly J Bower — 09/12/2016 Date

I acknowledge that my contribution to the above paper is 5%.

09/12/2016

Brooke Adair Date

I acknowledge that my contribution to the above paper is 5%.

09/12/2016

Yong-Hao Pua Date

I acknowledge that my contribution to the above paper is 5%.

09/12/2016

Gavin P Williams Date

I acknowledge that my contribution to the above paper is 5%.

09/12/2016

Rebekah McGaw Date

I acknowledge that my contribution to the above paper is 10%.

09/12/2016

Ross A Clark Date

Appendix F – Study One manuscript

The results from Study One have been published in *Brain Injury* (Mentiplay et al., 2015a). The publishers (Taylor & Francis) were contacted via email and they provided permission for the full text article to be included in this thesis. The article can be found in the following pages or on the publisher's website at:

http://www.tandfonline.com/doi/full/10.3109/02699052.2014.995231

BRAIN INJURY

http://informahealthcare.com/bij
ISSN: 0269-9052 (print), 1362-301X (electronic)

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 DOI: 10.3109/02699052.2014.995231

informa healthcare

REVIEW ARTICLE

Associations between lower limb strength and gait velocity following stroke: A systematic review

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Abstract

Objective: The aim of this systematic review was to identify literature examining associations between isometric strength and gait velocity following stroke.
Methods: An electronic search was performed using six online databases. Targeted searching of reference lists of included articles and three relevant journals was also performed. Two independent reviewers identified relevant articles, extracted data and assessed the methodological quality of included articles. Inclusion criteria involved studies that assessed univariate correlations between gait velocity and isometric strength of individual lower limb muscle groups in a stroke population.
Results: Twenty-one studies were included for review. The majority of included studies had a relatively small sample size. After accounting for sample size and methodological quality, the knee extensors showed poor-to-moderate correlations with gait velocity while the ankle dorsiflexors showed the strongest association with gait velocity.
Conclusions: Current evidence suggests that the strength of the ankle dorsiflexors has a stronger correlation to gait velocity compared with other lower limb muscle groups. Consequently, a focus on increasing ankle dorsiflexor strength to improve gait velocity following stroke may be beneficial. However, due to limitations of the research identified, further research is needed to determine the associations between lower limb strength and gait velocity following stroke.

Keywords

Gait speed, muscle strength, rehabilitation, review, stroke, walking

History

Received 8 April 2014
Accepted 20 November 2014
Published online 30 December 2014

Introduction

Stroke is one of the leading causes of disability worldwide [1], resulting in both acute and long-term limitations. Impairments such as muscle weakness, balance deficits, aerobic endurance and sensory changes can interact and impact on physical function following stroke [2–4]. While there are many methods to assess physical function following stroke, including the Timed Up and Go and the Six Minute Walk Test, the measure of gait velocity has been shown to be a discriminative clinical measure that can be predictive of length of hospital stay, functional outcome and community ambulation [5–7] and, therefore, may warrant further attention.

Although there are many contributors to gait velocity, muscle weakness has been proposed to be one of the primary factors associated with physical limitations and reduced gait velocity post-stroke [4, 8–10]. In order to manage and improve gait velocity and potentially improve functional outcomes, it may be important to understand the association between gait velocity and lower limb muscle strength. Biomechanical modelling has shown that in healthy populations the primary muscle groups contributing to forward progression are the ankle plantarflexors [11, 12], hip flexors and hip extensors [12, 13]. In individuals after stroke, laboratory-based analysis of ankle and hip power generation during the gait cycle has also been shown to correlate strongly with gait velocity [14, 15]. Despite limited evidence to support the role of the knee extensors in forward progression, a recent systematic review identified that many research-based intervention studies focused on improving the strength of the knee extensors as a means to improve gait [16]. Although the knee extensors are important for many functional activities, such as sit to stand ability [17], there is a discrepancy between those muscles considered most important for gait and those which are often targeted in clinical trials. This discrepancy might explain why strength training interventions in neurological populations often result in inconclusive improvements in gait performance [16]. Before implementing strength assessments and interventions, it could be helpful to understand the association between gait velocity and each of the muscle groups of the lower limb. This will

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ensure that the muscle groups that influence gait performance are examined and treated, which may, therefore, lead to improved functional outcomes.

The aim of this study was to review the literature examining the correlations between gait velocity and the strength of individual lower limb muscle groups in people after stroke. A systematic review approach was adopted to enable the rigorous collation and synthesis of existing data in this area in order to assist clinical decision-making and guide future research. It was hypothesized that the muscle groups responsible for forward progression would demonstrate excellent associations with gait velocity, whilst muscle groups that contribute little to forward progression, such as the knee extensors, would demonstrate poor associations.

Methods

Search strategy

An electronic database search was performed in August 2013 using Scopus, Medline, CINAHL, Web of Science, Embase and PubMed. Key search terms and relevant synonyms were kept consistent across all databases and, where possible, relevant medical subject headings were used. The search strategy for Medline and Web of Science are shown in Appendix 1. No limitations were placed on publication date. Targeted searching of the reference lists from included articles and three relevant journals (*Archives of Physical Medicine and Rehabilitation*, *Gait & Posture* and *Stroke*, from 2008 onwards) was also performed to identify any additional articles not located in the systematic database search.

Selection criteria

The selection criteria are displayed in Table I. Only original, full text research articles were examined. Due to the inability to accurately translate and assess non-English articles, only those published in English were included for review. Grey literature (e.g. book chapters) and conference abstracts were excluded due to the limited peer review processes they undergo before publication and review articles were excluded as they do not provide original research. All research designs were included, except for case studies due to their potential for bias and difficulty in generalizing the results to a larger population. In addition to including cross-sectional studies where the correlation was the primary focus, the selection criteria allowed other research designs to be included such as those developed to test the psychometric properties of a measurement tool or device, if the study also included correlation analysis of the data from the initial testing session. Articles were required to contain a univariate correlation between gait velocity and at least one measure of strength from the muscles surrounding a single joint of the lower limb. Studies which only reported correlations of the change between pre- and post-intervention measures of gait and strength were excluded as this predominantly provides information about the intervention.

For this review, strength measures were required to be an isometric test of an individual muscle group, regardless of the strength measurement device used. Measurement of isometric strength has demonstrated consistency between clinical and laboratory devices [18]. Additionally, hand-held dynamometry (HHD) has been shown to be a reliable measure of strength in neurological populations [19, 20] and can be easily used in a clinical setting. Strength of the paretic limb was the focus of this review; however, correlations involving the strength of the non-paretic limb are provided in Appendix 3. Dynamic or isokinetic tests were excluded as there is a lack of availability of these devices in the majority of hospital and rehabilitation clinics due to their expense and cumbersome nature [21]. Composite scores of lower limb strength were excluded as they provide no information of the strength of individual muscle groups.

Gait velocity was required to be measured over a short linear distance, regardless of the tool used to measure it (e.g. stopwatch or three-dimensional motion analysis), as these tools are typically highly related [22]. Measurement of gait velocity using a stopwatch has demonstrated high inter-rater and test–re-test reliability in adult neurological populations [23, 24]. Functional tests, such as the Timed Up and Go and the Six Minute Walk Test, were excluded because they assess and are influenced by other aspects of gait and functional performance such as sit to stand ability [25] and endurance [26], respectively.

Selection of articles

The title and abstract of each article in the initial yield was assessed for eligibility by one reviewer (author B.F.M.), and all non-stroke related articles were removed. The selection criteria were independently applied to the remaining articles by two independent reviewers (authors B.F.M. and G.T.). The final articles to be included were agreed upon by both reviewers, with differences resolved through discussion and mutual consensus. If consensus could not be reached, a third independent reviewer was consulted (author B.A.).

Table I. Selection criteria.

Inclusion criteria	Exclusion criteria
Human adult participants who have had a stroke	Correlation based on results from functional tests (e.g. Six Minute Walk Test or Timed Up and Go)
A measure of gait velocity over a short linear distance without any rest breaks	Dynamic or isokinetic tests of lower limb strength and composite scores of lower limb strength
A measure of isometric strength of a single lower limb joint	Regression analysis without a univariate correlation
A univariate correlation between gait velocity and strength	Correlations of change scores between pre- and post-intervention
	Grey literature, conference abstracts and review articles
	Case studies
	Published in languages other than English

DOI: 10.3109/02699052.2014.995231

Data extraction and quality assessment

Data were independently extracted by two reviewers (authors B.F.M. and G.T.) using a pre-determined, customized data extraction form. The data that were extracted included the characteristics of the study participants, the gait and strength outcome measures as well as the correlation results reported for each study. Correlation results were interpreted as poor (<0.50), moderate (0.50–0.75) and excellent (>0.75) [27].

Currently, there is a lack of consensus on the most appropriate measure of methodological quality in observational research [28, 29]. Many of the previously published quality assessment tools have been designed to assess the methodological quality of specific research designs and would, therefore, not necessarily meet the more heterogeneous design requirements of this particular review. A previous systematic review of correlational results utilized a customized tool specifically designed to assess the quality of correlation studies in people with Parkinson's disease [30]. The tool developed by Tan et al. [30] was based on relevant criteria from two other previously published quality assessment tools [31, 32]. Although the psychometric properties of this measure are yet to be determined, the design of the tool made it appropriate for use in the current review. Accordingly, the quality assessment tool developed by Tan et al. [30] was adapted for use in studies of people with stroke. For each question, an arbitrary score of 0 indicated low quality, 0.5 indicated medium quality and a score of 1 indicated high quality methodological reporting, with a maximum total score of 20 (Appendix 2). Guidelines have yet to be established regarding what can be considered acceptable or high methodological quality when using this tool. During the current review the included articles were compared to one another based on quality scores, as well as the different methodological components identified as being important for correlation studies. Quality assessment was performed independently by two reviewers (authors B.F.M. and G.T.). Any discrepancies for data extraction and quality assessment were resolved through discussion and mutual consensus. If consensus could not be reached, a third independent reviewer was consulted (author B.A.).

Results

The stages involved in identifying the eligibility of the articles are shown in Figure 1. The initial yield, after removal of duplicates, was 2598 articles. Twenty articles were identified as meeting the selection criteria [33–52], with one additional article [9] found during targeted searching. Seven articles were published by Bohannon and colleagues [9, 33–38]. There were concerns that the studies by Bohannon and colleagues may have included the same participants, therefore

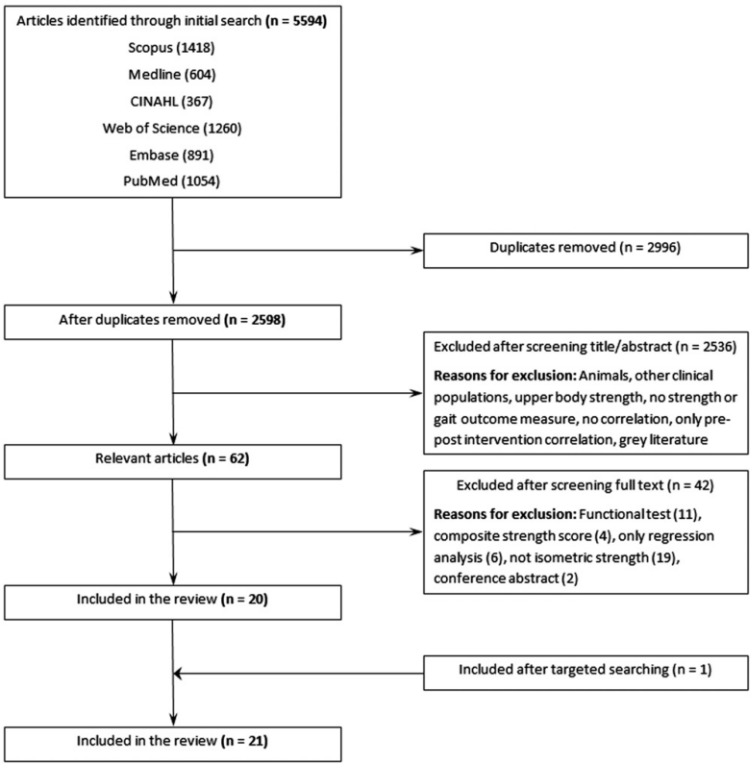

Figure 1. Flow diagram of search results.

Brain Inj, 2015; 29(4): 409–422

the primary author was contacted to provide clarification. Three studies involved unique samples [9, 35, 36], whilst four articles had some overlap in the sample [33, 34, 37, 38]. After contacting the author, the degree of overlap of the participants remained unclear. To prevent exclusion of important and new results, all seven articles by Bohannon and colleagues remained in the data extraction process. Nevertheless, the four studies that had some overlap in participants [33, 34, 37, 38] may provide similar results and, thus, should be compared cautiously with other studies.

Participant characteristics

Characteristics of the participants included in each article are displayed in Table II. Eleven studies had 20 or fewer participants [33, 34, 36–39, 41, 42, 48–50] and seven had 40 or more [40, 43, 44, 46, 47, 51, 52]. All but one study [48] included participants with a mean age greater than 50 years (mean age across all studies = 47.9–70.6 years), 66% of participants were male and 51% had a left hemiparesis, with one study not reporting the side of hemiparesis [49]. The time since stroke onset varied between and within studies, with the mean time ranging from 30.4 days up to 8.7 years (range = 4 days to 30.8 years). Only eight studies reported the type of stroke [41–43, 45–48, 52].

Outcome measures

The outcome measures utilized in each study are presented in Table II. Eighteen studies assessed gait velocity by using a stopwatch to time their participants walking over a short distance of between 5–10 metres [9, 33–43, 46–50, 52]. Three studies used laboratory-type measurement devices, being GAITRite (a spatiotemporal gait analysis mat) [44, 51] and a three-dimensional motion analysis system [45]. Fourteen studies asked participants to walk at their most comfortable speed [9, 33–35, 37, 40, 41, 43–46, 50–52], four asked them to walk as fast as safely possible [39, 42, 47, 49] and three performed trials at both speeds [36, 38, 48]. Gait velocity was determined using a variety of methods: seven articles used the average of three gait trials [41, 42, 44, 45, 50–52]; four articles used one trial [33, 36, 38, 46]; two articles used the average of two trials [35, 40]; two articles used the fastest of two trials [43, 47]; one article collected and analysed two trials [37] and the method was unable to be determined in four articles [9, 34, 39, 48]. One article used the fastest of three trials, however three of the participants only completed one trial, as their 10-metre walk test took longer than 30 seconds [49].

The usual assistive devices used by the participants, such as walking canes or orthoses, were allowed during the assessments in 13 studies [9, 33, 34, 36–39, 41, 43, 45, 48, 51, 52]. Four studies did not allow the use of any assistive device [40, 44, 49, 50] and four studies did not report whether assistive devices were allowed during testing [35, 42, 46, 47]. It should be noted that, in the studies which allowed assistive devices, not all participants necessarily used these devices during the assessment. Eleven studies used HHD to measure the strength of individual muscle groups [9, 33, 34, 40, 42–47, 50], nine studies used laboratory-based dynamometers [36–39, 41, 48, 49, 51, 52] and one study used a combination of both [35].

Associations between lower limb strength and gait velocity

Figure 2 provides a graphical representation of the correlations between the strength of individual muscle groups of the paretic limb and gait velocity. Additional information regarding the correlations is provided in Appendices 3 and 5. Thirteen articles exclusively measured the muscle groups of the knee [34–39, 41–43, 46, 47, 49, 52], three measured only ankle muscle groups [44, 48, 51] and five measured multiple muscle groups around the hip, knee and ankle [9, 33, 40, 45, 50]. Equivocal results were reported across the studies for correlations between gait velocity and the strength of the paretic hip flexors ($r = 0.25$–0.82) [9, 33, 40, 45, 50], hip extensors ($r = 0.29$–0.78) [9, 33, 40, 50], hip abductors ($r = 0.24$–0.80) [9, 33, 40], knee extensors ($r = 0.18$–0.81) [9, 33–43, 45–47, 49, 50, 52], knee flexors ($r = 0.30$–0.83) [9, 33, 40, 41, 50] and ankle plantarflexors ($r = 0.11$–0.83) [9, 33, 40, 44, 48, 50, 51]. In contrast, the strength of ankle dorsiflexors of the paretic limb consistently showed moderate-to-excellent correlations with gait velocity ($r = 0.50$–0.77) [9, 33,40, 44, 45, 50, 51]. One study also measured the correlation between gait velocity and the strength of the hip adductors ($r = 0.29$), hip internal rotators ($r = 0.30$), hip external rotators ($r = 0.22$), ankle invertors ($r = 0.25$) and ankle evertors ($r = 0.33$) [40]. The non-paretic limb showed poor-to-moderate correlations for each muscle group ($r = 0.05$–0.70) (Appendix 3) [9, 34–36, 38, 41, 46, 47, 49, 50].

Closer examination of the studies with the largest sample sizes [40, 43, 44, 46, 47, 51, 52] showed poor-to-moderate correlations between gait velocity and knee extensor strength ($r = 0.18$–0.55) [40, 43, 46, 47, 52] and ankle plantarflexor strength ($r = 0.29$–0.58) [40, 44, 51] on the paretic side. In contrast, the strength of ankle dorsiflexors of the paretic limb consistently showed moderate correlations with gait velocity ($r = 0.50$–0.73) [40, 44, 51].

Quality assessment

The methodological quality scores for each article are shown in Appendix 4. The mean total quality score was 11.6 (range = 7.6–15.3). Seven studies [40, 43, 44, 46, 47, 51, 52] demonstrated the highest methodological quality scores in combination with the largest sample sizes. When compared to the other articles in this review, the quality scores and larger sample sizes could indicate that these studies were at less risk of bias, potentially improving the generalizability of their results. Generally, articles described outcome measures and the main findings of the study well. Additionally, studies also reported the *r*-value for each correlation, summarized results with reference to objectives and used appropriate statistical tests. Overall, studies provided little to no information on the experience of the assessors. Efforts to address bias [52] and justification of sample size [43] were only reported in single articles.

Discussion

This systematic review found a broad range of associations between gait velocity and lower limb strength. The strength of

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Table II. Study characteristics.

Reference, Year	Sample size (M/F)	Mean age ± SD (range), years	Mean time since stroke ± SD (range)	Side of hemiparesis (Left/Right)	Type of stroke	Gait test used	Gait speed assessed	Mean gait velocity ± SD (range), ms^{-1}	Assistive devices used during assessment (*n*)	Strength device used
Bohannon [9], 1989	33 (15/18)	67.7 ± 11.1	30.4 ± 14.6 days	22/11	—	8 m walk	CGS	0.16 ± 0.24	Rolling walkers: quad canes; single point canes; AFO (total – 17)	HHD
Bohannon [33], 1986	20 (13/7)	60.8 ± 8.4	68 ± 46.6 (24–187) days	8/12	—	8 m walk	CGS	0.51 ± 0.42 (0.09–1.67)	Walkers (8); quad canes (6); single point canes (4); AFO (9)	HHD
Bohannon [34], 1989	12 (6/6)	64.4 ± 14.1 (33–78)	36.4 ± 10.7 (17–54) days	6/6	—	8 m walk	CGS	0.26 ± 0.29 (0.05–1.02)	Ambulatory aids; orthoses	HHD
Bohannon [35], 1991	26 (13/13)	58.4 ± 11.7 (33–84)	69.5 ± 70.6 (14–320) days	12/14	—	8 m walk	CGS	0.37 ± 0.34	?	HHD Cybex
Bohannon [36], 1992	20 (10/10)	63.7 ± 14.9 (28–82)	70 ± 109 (4–364) days	14/6	—	7 m walk	CGS FGS	—	—	Lido Active
Bohannon and Andrews [37], 1990	17 (11/6)	59 ± 11.4 (33–84)	51 ± 41.8 (15–198) days	7/10	—	8 m walk	CGS	0.34 ± 0.33	—	Cybex
Bohannon and Walsh [38], 1992	14 (6/8)	68.1 ± 11 (48–83)	54.5 ± 93.3 (4–347) days	4/10	—	7 m walk	CGS FGS	—	Physical assistance for balance (2); single point canes or quad canes (7); close supervision no physical assistance (5)	Lido Active
Davies et al. [39], 1996	12 (8/4)	59 ± 18 (24–75)	17 ± 12 (3–42) months	3/9	—	10 m walk	FGS	0.61 ± 0.07	Walking aid (4)	Lido Active
Dorsch et al. [40], 2012	60 (42/18)	69 ± 11	1–6 years	28/32	—	10 m walk	CGS	0.75 ± 0.34 (0.09–1.41)	No assistive devices	HHD
Horstman et al. [41], 2008	14 (10/4)*	55.9 ± 10.4	109 ± 46 days	6/8	5 Hem 9 Isch	10 m walk	CGS	0.30 ± 0.17	—	LEXS
Kobayashi et al. [42] 2011	10 (10/0)	54.3 ± 8.4	8.7 ± 4.5 years	5/5	6 Hem 4 Isch	5 m walk	FGS	0.75 ± 0.19 (0.50–1.14)	?	HHD
Lam et al. [43], 2010	45 (27/18)	67.7 ± 11.3 (42–90)	<6 months	25/20	7 Hem 38 Isch	6 m walk	CGS	0.49 ± 0.31 (0.06–1.20)	Canes (22); quad canes (9); frame (5)	HHD
Lin et al. [44], 2006	68 (52/16)	61.69 ± 13.97 (31–82)	3.91 ± 5.87 (0.02–30.78) years	26/42	—	GAITRite	CGS	0.65 ± 0.32 (0.04–1.49)	No assistive devices	HHD
Lin [45], 2005	21 (15/6)	65.2 ± 9.1	63.2 ± 55.5 months	13/8	9 Hem 12 Isch	10 m walk (3DMA)	CGS	—	Single point canes (1); quad canes (9)	HHD
Liu-Ambrose et al. [46], 2007	63 (37/26)	65 ± 9 (52–87)	6 ± 5 (1–28) years	41/22	37 Isch	10 m walk	CGS	0.8 ± 0.4 (0.1–2.1)	?	HHD
Maeda et al. [47], 2000	40 (21/19)	M: 69.6 ± 8.3 F: 70.6 ± 9.1	2.9–3.8 years	20/20	35 Hem 5 Isch	10 m walk	FGS	M: 0.69 ± 0.34 F: 0.67 ± 0.41	?	HHD
Nadeau et al. [48], 1997	16 (12/4)	47.9 ± 15.6 (18–73)	43.9 ± 36.5 (2–105) months	4/12	5 Hem 8 Isch 3 Unspec	9 m walk	CGS FGS	CGS: 0.76 ± 0.27 (0.41–1.50) FGS: 1.08 ± 0.33 (0.58–1.76)	Single point canes (4)	Biodex
Nakamura et al. [49], 1985	11 (10/1)	M: 53.8 (27–77) F: 50	4 (0.5–22.5) months	—	—	10 m walk	FGS	0.92 ± 0.58 (0.16–1.92)	No assistive devices	Cybex
Nasciuti-Prudente et al. [50], 2009	12 (6/6)	70.57 ± 3.31 (65–75)	2.51 ± 2.82 (0.58–11) years	4/8	—	10 m walk	CGS	0.65 ± 0.33 (0.15–1.31)	No assistive devices	HHD
Ng and Hui-Chan [51], 2012	62 (51/11)	57.4 ± 7.8 (45–78)	5.2 ± 3.7 years	43/19	—	GAITRite	CGS	0.52 ± 0.26 (0.13–1.10)	Single point canes (62)	Load Cell
Severinsen et al. [52], 2011	48 (35/13)	68 ± 9 (50–80)	18 ± 6 (8–38) months	22/26	68 non-hem	10 m walk	CGS	0.84 ± 0.3	—	Biodex

M, male; F, female; SD, standard deviation; m s^{-1}, metres per second; CGS, comfortable gait speed; FGS, fast gait speed; AFO ankle foot orthoses; Hem, haemorrhagic; Isch, ischaemic; Unspec, unspecified; —, unable to determine the assistive devices used; ?, not mentioned if assistive devices were allowed; *, three participants could not perform gait test; hence, were not used for analysis; HHD, hand-held dynamometer; Lido Active, Lido Active Rehabilitation System; LEXS lower extremity system; Cybex, Cybex isokinetic dynamometer; Biodex, Biodex system dynamometer; 3DMA, three-dimensional motion analysis; GAITRite, GAITRite walkway system.

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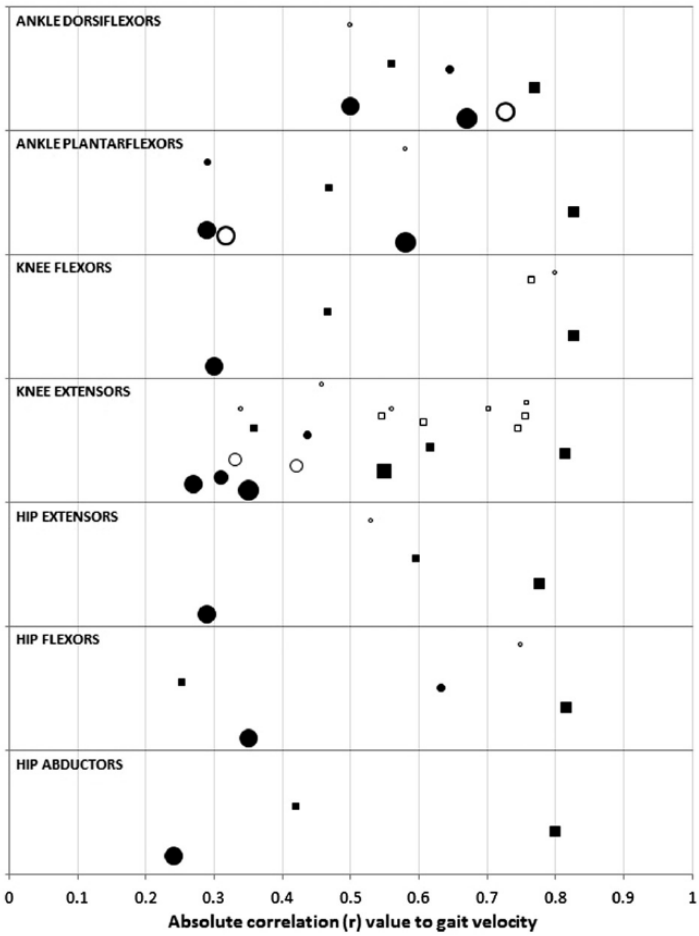

Figure 2. Associations between the strength of individual muscle groups of the paretic lower limb and gait velocity. All correlations are between the strength of the paretic lower limb and gait velocity. All correlations are reported as absolute values. The size of the point indicates the sample size, with a larger point indicating higher sample size. The *y*-axis is arranged so that low sample size studies are towards the top of each muscle group section. Circular points indicate participants with a mean time since stroke of more than 6 months and square points indicate a mean time since stroke of less than 6 months. Solid points indicate the strength scores were normalized and open points indicate the strength scores were not normalized. One correlation per muscle group from each study is provided in this figure, with a more detailed description of the correlations provided in Appendices 3 and 5. The associations between gait velocity and the strength of the hip adductors ($r = 0.29$), hip internal rotators ($r = 0.30$), hip external rotators ($r = 0.22$), ankle invertors ($r = 0.25$) and ankle evertors ($r = 0.33$) have not been included in this figure [40]. These associations were assessed in only one study and have been excluded to enhance the overall readibility of the figure.

the ankle dorsiflexors on the paretic side was found to have the strongest association with gait velocity when compared to other muscle groups. However, only three of the seven articles with a larger sample size and higher quality score [40, 44, 51] measured muscle groups around the ankle. The majority of the literature assessed the correlations between gait velocity and the strength of only one muscle group. The comparison of results between multiple muscle groups could assist in interpreting the relative importance of different muscle groups to gait post-stroke. The knee extensors were the most commonly measured muscle group. The strength of the knee extensors demonstrated poor-to-moderate correlations with gait velocity in those seven articles with a larger sample size and higher methodological quality. The results of this review did not support the hypothesis that the strength of the muscle groups most responsible for forward progression would show the strongest associations with gait velocity. However, many of the included studies demonstrated incomplete reporting and inconsistencies with their methodology, suggesting caution when interpreting the results and highlighting the need for further research.

The moderate-to-excellent correlations between gait velocity and the strength of the ankle dorsiflexors was an unexpected finding. The ankle dorsiflexors act during the swing phase of gait to help with ground clearance of the foot [53, 54] and eccentrically during loading response after heel strike [51, 54]. Weakness of the ankle dorsiflexors can lead to compensatory movements, such as leg circumduction and hip hiking, to allow for foot clearance during gait [53, 54], therefore increasing swing time and potentially resulting in a reduction in overall gait velocity [40]. Evidence suggests that the strength of the ankle dorsiflexors has a strong association with stair climbing ability, the Timed Up and Go and Six Minute Walk Test post-stroke [51, 55, 56], supporting the importance of this muscle group in other functional activities. The moderate-to-excellent association between gait velocity and the strength of the ankle dorsiflexors indicates that it may be pertinent to prioritize measuring their strength in routine

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clinical assessment following stroke. Nevertheless, these results come from three studies [40, 44, 51], two of which [44, 51] only measured the ankle dorsiflexors and plantarflexors. It is recommended that future studies measure multiple lower limb muscle groups to provide a comparison of the associations between the strength of lower limb muscle groups and gait velocity following stroke.

Despite contributing to forward progression during gait, the strength of the ankle plantarflexors, hip flexors and hip extensors was not strongly associated with gait velocity when compared to other lower limb muscle groups. These muscle groups, however, were infrequently measured (reported in seven, five and four articles respectively), complicating the interpretation of the overall results and indicating that further research is required. Additionally, out of the seven articles with higher sample sizes and methodological quality scores, only three articles measured the ankle plantarflexors [40, 44, 51] and one article measured the hip flexors and extensors [40], again highlighting the need for further targeted, high quality research in these potentially important muscle groups. The knee extensors were the most commonly measured muscle group (reported in 18 articles). Four studies, with a relatively large sample size and higher methodological quality scores (range = 45–63, 12.8–15.3, respectively) showed a trend towards poor-to-moderate correlations between the strength of the knee extensors and gait velocity, supporting the original hypothesis [40, 43, 46, 52]. This limited association might help to explain the findings of a recent systematic review, which showed that, while the majority of strength training interventions in neurological rehabilitation focused on the knee extensors, most of these interventions failed to result in significant improvements in gait performance [16]. Despite this finding, the strength of the knee extensors has been associated with performance in other functional tasks post-stroke, such as stair climbing [55, 57] and sit-to-stand ability [17]. The association between the strength of the knee extensors and the performance of other functional tasks suggests that these muscles should not be overlooked in assessment and treatment following stroke when aiming to achieve improvements in activities other than walking. The findings from the current review imply that, to target functional gait improvements, it may be warranted for researchers and clinicians to emphasize the assessment and training of the ankle dorsiflexors and not just solely the knee extensors.

Thirteen of the studies identified during this review included participants who required some form of assistive device to mobilize. The use of assistive devices, especially ankle foot orthoses, can change the contributions a muscle makes during gait [40]. Even the use of simple assistive devices, such as walking canes, can influence kinematic and spatial variables during gait, thus potentially affecting the correlations between strength and gait velocity [58]. Comparison between those articles that allowed assistive devices to be used during assessment against those that did not allow assistive devices was not feasible. The articles that allowed assistive devices during the assessment pooled the results of all participants, despite not all participants using such devices. This may detract from the generalizability of the results from those articles that did not account for the use of mobility devices in their analyses. The allowance of assistive devices during the assessment of gait velocity may have resulted in the inclusion of participants with more severe physical deficits; therefore, making the samples more representative of the wider population of stroke survivors in the community. Nonetheless, the inclusion of these data without further clarification of details regarding the use of assistive devices indicates caution may be needed when interpreting the results. Moreover, the analysis and presentation of pooled results when there was variability in the participant characteristics limited the ability to perform sub-group analyses and may restrict the generalizability of the results to populations of stroke survivors with specific characteristics.

The speed at which the participants were asked to walk and the strength device used varied between the studies. Participants either performed the gait tests at a comfortable pace or as fast as safely possible. Three studies asked their participants to perform the gait test at both speeds [36, 38, 48] and found little difference between the correlations for the different paces. However, the small sample size in these three studies ($n \leq 20$) negated the ability to assess the differences in correlations between the studies for the two gait speeds. Regarding the strength assessment device, one study used both a clinical and laboratory-based measure of muscle strength and found minimal differences in the correlation to gait velocity between the strength measurement devices [35]. This may indicate that it is adequate to use clinically-based measures of muscle strength when examining the correlations between muscle strength and gait velocity post-stroke. However, further targeted, high quality research is needed to determine if the correlations between the strength of individual muscle groups and gait velocity are altered depending on the speed of the gait tests and the strength assessment device used.

This review did not examine isokinetic strength assessment, which could provide additional information on the associations between lower limb muscle strength and gait velocity. Previous research examining the associations between isokinetic strength and gait velocity, with a sample size of at least 50, has found similar results to this review, with isokinetic knee extensor strength being moderately correlated with gait velocity [57, 59]. Due to the need for expensive and cumbersome motorized dynamometers to test isokinetic strength, these studies were excluded as many hospitals and rehabilitation centres do not have access to such devices. Additionally, a recent systematic review [18] identified that HHD, due to its low cost, portability, ease of use and moderate-to-good reliability and validity when compared with isokinetic testing, could be considered a practical, clinical standard for strength assessment.

A major limitation of many of the studies identified in this review is their small sample size. Including a reasonable sample size in correlation studies is important so that the study is statistically powered to detect a significant correlation [27]. According to Portney and Watkins [27] a sample size of 28 is needed to detect a moderate relationship (r-value of 0.50), powered at 80% with a two tailed significance level of 0.05. Only eight of the 21 studies included a sample size above 28 [9, 40, 43, 44, 46, 47, 51, 52], with only one study providing a power calculation for their sample [43]. As such,

more weight could be placed on the results from these eight studies as they were adequately powered to detect a significant correlation. However, it was difficult to compare the results of these studies due to the heterogeneous participants (e.g. the time since stroke) and methods (e.g. the muscle groups assessed) between each study.

A clear description of the characteristics of the participants allows clinicians and researchers to adequately interpret and generalize the results. Many of the included studies failed to report the type of stroke (i.e. haemorrhagic or ischaemic). Additionally, the reliability of the strength measurement device used and/or the assessor was rarely reported (six articles only), which is particularly important for strength assessment using HHD. While this review highlighted some important findings regarding the associations between muscle strength and gait velocity, further research is required. It would be beneficial for future correlation studies to ensure a complete description of participant characteristics, measure multiple lower limb muscle groups rather than single muscles and provide reliability results of their strength assessor to address some of the inconsistencies in the current literature.

It should be noted that one article published by Ng and Hui-Chan [51] included only participants with ankle spasticity, potentially limiting the generalizability of their results to the wider stroke population. The results from this article [51] found similar correlations to those found in other studies [40, 44], despite inclusion of participants with differing characteristics. The other two articles [40, 44] measured the same muscle groups and also had a similar sample size to the article published by Ng and Hui-Chan [51], indicating that ankle spasticity may not affect the correlations between muscle strength and gait velocity. However, further targeted research is needed to conclusively determine the impact of spasticity on correlations between muscle strength and gait velocity following stroke.

The current review is the first to collate literature examining the correlations between lower limb strength and gait velocity following stroke and provides a basis for future research in this important rehabilitation area. Due to the large variability within and between the articles included in this review, it may be problematic to analyse and compare any sub-groups within the results (e.g. comparing differences in correlations between people based on the use of assistive devices or time since stroke). However, this review could be used to inform future research examining the correlations between lower limb muscle strength and gait velocity following stroke.

Study limitations

It would be erroneous to imply that the muscles of the lower limb work in isolation and that weakness in one muscle group is solely responsible for reduced gait velocity following stroke [60]. Nonetheless, before attempting to understand the contribution of other factors (such as balance and proprioception) to gait velocity, it may be important to first investigate the associations between gait velocity and single variables, such as the strength of individual muscle groups. Although the results from a HHD may not be as accurate as laboratory dynamometers, they are a low cost, readily available device that is commonly used in a clinical setting and, therefore, warranted further investigation with this study.

The development of this study's own customized quality assessment tool, without testing the psychometric properties of this tool, is a limitation of the current review. At the time of this review there was a lack of an appropriate tool to assess the methodological quality of articles with various research designs that examine correlations, necessitating the modification and use of the tool described by Tan et al. [30]. The inclusion of articles with heterogeneous participant characteristics (time since stroke and use of assistive devices) may be problematic due to the inability to make direct comparisons between the included articles. This review is the first to assemble and compare results from articles examining the associations between muscle strength and gait velocity following stroke and as such it was decided to include all articles regardless of their participant characteristics. The results from this initial step in understanding the impact of muscle strength on gait velocity might help to guide the assessment and treatment plans for clinicians and researchers and create a solid platform for future research.

Conclusion

The measurement of lower limb strength following stroke is an important clinical consideration that is often implemented in research and clinical practice. Whilst this review suggests the strength of the ankle dorsiflexors to have a stronger correlation to gait velocity than other muscle groups, the results should be interpreted with caution due to limitations in the included articles. Further research is needed to determine the association and effect of muscle weakness on gait velocity and the differences in correlations between various subgroups within the stroke population.

Declaration of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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Appendix 1

Search strategy for Medline and Web of Science.

Medline

#1 (MH 'Cerebral Haemorrhage') OR (MH 'Brain Infarction') OR (MH 'Cerebral Infarction') OR (MH 'Intracranial Haemorrhages') OR (MH 'Brain Ischaemia') OR (MH 'Stroke')
#2 (MH 'Muscle Strength' OR (MH 'Muscle Strength Dynamometer') OR (MH 'Muscle Contraction') OR (MH 'Isometric Contraction')
#3 (MH 'Gait') OR (MH 'Locomotion') OR (MH 'Walking')
#4 AB (stroke OR (cerebrovascular accident) OR CVA OR (cerebral infarct*) OR (brain infarct*) OR (intracranial haemorr*) OR (intra-cranial haemorr*) OR (intracranial hemorr*) OR (intra-cranial hemorr*) OR (cerebral haemorr*) OR (cerebral hemorr*) OR (cortical haemorr*) OR (cortical hemorr*) OR (cortical ischaem*) OR (cortical ischem*) OR (cerebral ischaem*) OR (cerebral ischem*) OR (brain ischaem*) OR (brain ischem*)) OR TI (stroke OR (cerebrovascular accident) OR CVA OR (cerebral infarct*) OR (brain infarct*) OR (intracranial haemorr*) OR (intra-cranial haemorr*) OR (intracranial hemorr*) OR (intra-cranial hemorr*) OR (cerebral haemorr*) OR (cerebral hemorr*) OR (cortical haemorr*) OR (cortical hemorr*) OR (cortical ischaem*) OR (cortical ischem*) OR (cerebral ischaem*) OR (cerebral ischem*) OR (brain ischaem*) OR (brain ischem*))
#5 AB (strength* OR (muscle strength*) OR (muscle contract*) OR power OR (muscle force) OR MVC OR (max* volunt* contract*) OR dynamo* OR isometric* OR isokinetic*) OR TI (strength* OR (muscle strength*) OR (muscle contract*) OR power OR (muscle force) OR MVC OR (max* volunt* contract*) OR dynamo* OR isometric* OR isokinetic*)
#6 AB (gait OR mobility OR walk* OR ambulat* OR locomot*) OR TI (gait OR mobility OR walk* OR ambulat* OR locomot*)
#7 #1 OR #4
#8 #2 OR #5
#9 #3 OR #6
#10 #8 AND #9
#11 #7 AND #10 (Limiters – English Language; Human)

Web of Science

#1 Topic = (stroke OR (cerebrovascular accident) OR CVA OR (cerebral infarct*) OR (brain infarct*) OR (intracranial haemorr*) OR (intra-cranial haemorr*) OR (intracranial hemorr*) OR (intra-cranial hemorr*) OR (cerebral haemorr*) OR (cerebral hemorr*) OR (cortical haemorr*) OR (cortical hemorr*) OR (cortical ischaem*) OR (cortical ischem*) OR (cerebral ischaem*) OR (cerebral ischem*) OR (brain ischaem*) OR (brain ischem*)) OR Title = (stroke OR (cerebrovascular accident) OR CVA OR (cerebral infarct*) OR (brain infarct*) OR (intracranial haemorr*) OR (intra-cranial haemorr*) OR (intracranial hemorr*) OR (intra-cranial hemorr*) OR (cerebral haemorr*) OR (cerebral hemorr*) OR (cortical haemorr*) OR (cortical hemorr*) OR (cortical ischaem*) OR (cortical ischem*) OR (cerebral ischaem*) OR (cerebral ischem*) OR (brain ischaem*) OR (brain ischem*))
#2 Topic = (strength* OR (muscle strength*) OR (muscle contract*) OR power OR (muscle force) OR MVC OR (max* volunt* contract*) OR dynamo* OR isometric* OR isokinetic*) OR Title = (strength* OR (muscle strength*) OR (muscle contract*) OR power OR (muscle force) OR MVC OR (max* volunt* contract*) OR dynamo* OR isometric* OR isokinetic*)
#3 Topic = (gait OR mobility OR walk* OR ambulat* OR locomot*) OR Title = (gait OR mobility OR walk* OR ambulat* OR locomot*)
#4 #3 AND #2
#5 #4 AND #1
#6 #4 AND #1 (Refined by: Languages = (English) AND [excluding] Document Types = (Review OR Book Chapter OR Letter OR Editorial Material OR Meeting Abstract OR Note))

MH, Medical subject heading (MeSH); AB, abstract; TI, title.

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Appendix 2

Methodological quality assessment tool.

Reporting	Guidelines
1. Were the research aims/questions/hypotheses stated clearly?	0 – Unclear as to the aim of the study 0.5 – Only aims with no hypotheses 1 – Everything clearly stated
2. Were inclusion and exclusion criteria clearly described?	0 – Unclear as to the criteria used in the study 0.5– Limited description 1 – Clear as to the criteria for inclusion/exclusion
3. Were gait and strength measures clearly described?	0 – Neither measure clearly described 0.5– Only one measure described 1 – Both clearly described
4. Were participant characteristics detailed adequately? (Sample Size, Age, Time since stroke, Type of stroke, Side of hemiparesis)	1 point per sub-category (1 – it was included, 0 – it was not included). Add together divide by number of sub-categories (5 in this case)
5. Are the main findings of the study clearly described?	0 – Main findings unclear 0.5 – Limited description of the main findings 1 – Clearly described
6. Does the study provide estimates of the random variability in the data for the strength and gait measures?	0 – No measures of variability provided for both tests 0.5 – Only SD or only range provided for one test 1 – Provides a measure of the total variability (SD and range) for both strength and gait
7. Is the *r*-value of each individual correlation reported?	0 – Not reported for each individual correlation 0.5 – Only reported for a few, not all 1 – Reported for each individual correlation
8. Is the significance (*p* value) reported for each correlation?	0 – *p* value not reported for each correlation 0.5 – *p* value reported as * ($p<0.05$) 1 – *p* value reported for each correlation
9. Were the key results summarized with reference to study objectives	0 – Results not summarized and no reference to study objectives 0.5 – Somewhat summarized 1 – Results summarized with reference to study objectives
10. Were clinical implications of the research stated?	0 – No clinical implications stated 0.5 – Clinical implications unclear 1 – Clinical implications stated
11. Were the limitations of the study discussed?	0 – No limitations mentioned 0.5 – Limitations briefly discussed, missing obvious limitations 1 – Limitations clearly discussed
External Validity	
12. Were those subjects who were prepared to participate representative of the population from which they were recruited?	0 – No (e.g. only people who responded to ads or flyers) 1 – Yes 0 – Not documented or unable to determine
Internal Validity	
13. Were the main statistical tests used to assess the main outcomes appropriate?	0 – Statistics used are inappropriate 1 – Appropriate statistics used for correlation (e.g. Pearson or Spearman)
14. Was the reliability of the tool used to measure strength stated?	0 – Not stated 1 – Stated the reliability of the tool with references or tested it themselves
15. Was the reliability of the assessor who measured strength stated?	0 – Not tested 1 – Assessed reliability of assessor and reported values (e.g. ICC)
16. Was information provided on the training and/or experience of the assessor?	0 – No information provided 1 – Gave information on the training and/or experience of the assessor
17. Were any efforts to address potential source of selection bias described?	0 – Not mentioned 1 – Mentioned attempts to reduce selection bias
18. Was there adequate adjustment for confounding in the gait analyses from which the main findings were drawn?	0 – Allowed to use AFO or walking device during test and analysis performed with non-assisted participants 1 – Nobody used AFO or walking device during tests OR allowed to use AFO then they were removed from analysis 0 – Not documented or unable to determine
Power	
19. Was the sample size justified?	0 – No sample size calculation performed 1 – Sample size calculation for correlation performed
20. Was the sample size at 28 or above, which is needed to detect a moderate correlation (*r*-value of 0.50), powered at 80% with a 2-tailed significance level of 0.05?	0 – Sample size was below 28 1 – Sample size was 28 or above

SD, standard deviation; ICC, intra-class correlation coefficient; AFO, ankle foot orthoses.

Appendix 3

Correlations between gait velocity and isometric lower limb strength of both limbs.

Reference, year	Gait test used	Gait speed assessed	Strength device used	Muscles tested	Joint angle	Sample size	Correlation to gait velocity (N - P)	Correlation to gait velocity (nN - nP)	Correlation to gait velocity (N - nP)	Correlation to gait velocity (nN - nP)
Bohannon [9], 1989	8 m walk	CGS	HHD†‡ (measured twice, initial values provided)	HF, HE, HAB, KE, KF, AP, AD	HF/HE – Hip flexed to 90° HAB – Hip extended KE/KF – Knee flexed to 90° AP/AD – ankle at 90°	33	HF: 0.815*** HE: 0.776*** HAB: 0.799*** KE: 0.813*** KF: 0.826*** AP: 0.827*** AD: 0.769***	—	HF: 0.514** HE: 0.410 HAB: 0.511** KE: 0.568*** KF: 0.423 AP: 0.438 AD: 0.427	—
Bohannon [33], 1986	8 m walk	CGS	HHD†	HF, HE, HAB, KE, KF, AP, AD	HF/HE – Hip flexed to 90° HAB – Hip extended KE/KF – Knee flexed to 90° AP/AD – ankle at 90°	20	HF: 0.252 HE: 0.595* HAB: 0.419 KE: 0.357 KF: 0.466* AP: 0.468* AD: 0.559*	—	—	—
Bohannon [34], 1989	8 m walk	CGS	HHD	KE	KE – knee at 90°	12	—	KE: 0.702	—	KE: 0.545
Bohannon [35], 1991	8 m walk	CGS	HHD† (Force) (cTorq) and Cybex (mTorq)	KE	KE – knee at 95°	26	KE Force: 0.616*** KE cTorq: 0.654*** KE mTorq: 0.677***	KE Force: 0.603** KE cTorq: 0.629*** KE mTorq: 0.654***	KE Force: 0.052 KE cTorq: 0.141 KE mTorq: 0.200	KE Force: 0.147 KE cTorq: 0.196 KE mTorq: 0.245
Bohannon [36], 1992	7 m walk	CGS FGS	Lido Active	KE	KE – knee at 90°	20	—	KE-CGS: 0.747*** KE-FGS: 0.744***	—	KE-CGS: 0.524* KE-FGS: 0.448*
Bohannon and Andrews [37], 1990	8 m walk	CGS	Cybex‡ (measured on 2 days, twice each day)	KE	KE – knee at 90°	17	—	KE d1m1: 0.605* KE d1m2: 0.539* KE d2m1: 0.564* KE d2m2: 0.575*	—	—
Bohannon and Walsh [38], 1992	7 m walk	CGS FGS	Lido Active	KE	KE – knee at 90°	14	—	KE-CGS: 0.667** KE-FGS: 0.755**	—	KE-CGS: 0.467 KE-FGS: 0.499
Davies et al. [39], 1996	10 m walk	FGS	Lido Active	KE	Knee at 90°	12	—	KE: 0.56	—	—

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Dorsch et al. [40], 2012	10 m walk	CGS	HHD†	HF, HE, HIR, HER, HAB, HAD, KE, KF, AP, AD, AI, AE	HF/HIR, HER/HAB, KE/KF. AP/AD, AI, AE – Hips and Knee at 90° HE – Hip at 0° HAD – Hip and Knee in flexion with foot resting on plinth	60	HF: 0.35* HE: 0.29* HIR: 0.30* HER: 0.22 HAB: 0.24 HAD: 0.29* KE: 0.27* KF: 0.30* AP: 0.29* AD: 0.50** AI: 0.25 AE: 0.33*	—	—	—	
Horstman et al. [41], 2008	10 m walk	CGS	LEXS	KE, KF	KE/KF – Knee at 60°	14§	—	KE: −0.545 KF: −0.763**	—	KE: −0.699* KF: −0.634*	
Kobayashi et al. [42], 2011	5 m walk	FGS	HHD	KE	KE – Knee at 90°	10	—	KE: 0.459*	—	—	
Lam et al. [43], 2010	6 m walk	CGS	HHD†	KE	KE – Knee at 90°	45	KE: 0.55**	—	—	—	
Lin et al. [44], 2006	GAITRite	CGS	HHD†	AP, AD	Ankle in neutral	68	AP: 0.58** AD: 0.67**	—	—	—	
Lin [45], 2005	10 m walk (3DMA)	CGS	HHD†	HF, KE, AD	Standardized to previous protocol	21	HF: 0.633** KE: 0.436* AD: 0.645**	—	—	—	
Liu-Ambrose et al. [46], 2007	10 m walk	CGS	HHD‖	KE	Knee at 90°	63	KE: 0.35**	—	KE: 0.15	—	
Maeda et al. [47], 2000	10 m walk	FGS	HHD	KE	Sitting position	40	—	M KE: −0.42** F KE: −0.33	—	M KE: −0.41** F KE: −0.43**	
Nadeau et al. [48], 1997	9 m walk	CGS FGS	Biodex†	AP	Ankle at 10° of AP	16	AP-CGS: 0.25 AP-FGS: 0.29	AP-CGS: 0.11 AP-FGS: 0.18	—	—	
Nakamura et al. [49], 1985	10 m walk	FGS	Cybex (Isometric at 3 knee angles)	KE	KE – Knee at 30°, 60° and 90°	11	—	KE90: 0.759** KE60: 0.749** KE30: 0.595	—	KE90: 0.436 KE60: 0.195 KE30: 0.175	
Nasciutti-Prudente et al. [50], 2009	10 m walk	CGS	HHD	HF, HE, KE, KF, AP, AD	HF, KE, AD – Seated position HE, KF, AP – Lying prone	12	—	HF: 0.75* HE: 0.53 KE: 0.34 KF: 0.80* AP: 0.58* AD: 0.50	—	HF: 0.26 HE: 0.38 KE: 0.19 KF: 0.34 AP: 0.45 AD: −0.13	
Ng and Hui-Chan [51], 2012	GAITRite	CGS	Load Cell mounted on a foot frame	AP, AD	Ankle in neutral position	62	—	AP: 0.318* AD: 0.727**	—	—	
Severinsen et al. [52], 2011	10 m walk¶	CGS	Biodex¶	KE	Knee extended	48	KE: 0.31*	KE: 0.18	—	—	

N, normalized; nN, not normalized; P, paretic limb; nP, non-paretic limb; CGS, comfortable gait speed; FGS, fast gait speed; HHD, hand-held dynamometer; Lido Active, Lido Active Rehabilitation System; LEXS, lower extremity system; Cybex, Cybex isokinetic dynamometer; Biodex, Biodex system dynamometer; 3DMA, three-dimensional motion analysis; GAITRite, GAITRite walkway system; cTorq, calculated torque; mTorq, measured torque; M, male; F, female; HF, hip flexors; HE, hip extensors; HIR, hip internal rotators; HER, hip external rotators; HAB, hip abductors; HAD, hip adductors; KE, knee extensors; KF, knee flexors; AP, ankle plantarflexors; AD, ankle dorsiflexors; AI, ankle invertors; AE, ankle evertors; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$; †normalized to body mass; ‡measured on multiple days, only initial assessment correlation is reported here; §three participants could not perform gait test; hence, were not used for analysis; ‖normalized to body mass and height; ¶normalized to expected value using age, height and sex adjusted regression equations from healthy populations; —, not measured.

Appendix 4

Methodological quality assessment scores.

Article	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total
Bohannon [9]	1	0.5	1	0.8	1	0	1	0.5	1	0.5	0	0	1	1	0	0	0	0	0	1	10.3
Bohannon [33]	0.5	0.5	1	0.8	1	1	1	0.5	1	1	0	0	1	0	0	0	0	0	0	0	9.3
Bohannon [34]	0.5	0.5	1	0.8	0.5	0.5	1	0	1	0.5	0	0	1	1	1	0	0	0	0	0	9.3
Bohannon [35]	1	1	1	0.8	1	0.5	1	0.5	1	1	0.5	0	1	1	1	1	0	0	0	0	13.3
Bohannon [36]	0.5	1	1	0.8	1	0.5	1	1	1	0.5	0.5	0	1	1	1	0	0	0	0	0	11.8
Bohannon and Andrews [37]	1	1	1	0.8	1	0.5	1	0.5	1	1	1	0	1	1	1	0	0	0	0	0	12.8
Bohannon and Walsh [38]	0.5	1	1	0.8	1	0.5	1	0.5	1	0.5	1	0	1	1	1	0	0	0	0	0	11.8
Davies et al. [39]	0.5	0.5	1	0.8	1	0.5	1	0	1	0.5	0.5	0	1	0	0	0	0	0	0	0	8.3
Dorsch et al. [40]	0.5	1	1	0.8	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	1	15.3
Horstman et al. [41]	1	1	1	1	1	0.5	1	0.5	1	1	0	0	1	0	0	0	0	0	0	0	10
Kobayashi et al. [42]	0.5	1	1	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	12.5
Lam et al. [43]	0.5	1	1	1	1	1	1	1	1	1	1	0	1	0	0	1	0	0	1	1	14.5
Lin et al. [44]	0.5	1	1	0.8	1	1	1	0.5	1	1	0.5	0	1	1	0	0	0	1	0	1	13.3
Lin [45]	0.5	1	1	1	1	0.5	1	0.5	1	1	0.5	0	1	0	0	0	0	0	0	0	10
Liu-Ambrose et al. [46]	0.5	1	1	0.8	1	1	1	0.5	1	1	1	0	1	1	0	0	0	0	0	1	12.8
Maeda et al. [47]	0.5	0.5	1	1	1	0.5	1	0.5	1	1	0.5	0	1	1	0	0	0	0	0	1	11.5
Nadeau et al. [48]	1	0.5	1	1	1	1	1	0.5	1	0.5	0.5	0	1	1	0	0	0	0	0	0	11
Nakamura et al. [49]	0.5	0	1	0.6	1	0.5	1	0.5	1	0.5	0	0	0	0	0	0	0	1	0	0	7.6
Nasciutti-Prudente et al. [50]	0.5	1	1	0.8	1	1	1	0.5	1	1	1	0	1	1	0	0	0	1	0	0	12.8
Ng and Hui-Chan [51]	0.5	1	1	0.8	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	1	12.3
Severinsen et al. [52]	1	1	1	1	1	0.5	1	0.5	1	1	1	1	1	0	0	0	1	0	0	1	14

Refer to Appendix 2 for each question involved in the methodological quality assessment scores.

Appendix 5
Additional description of Figure 2

To ensure Figure 2 is as clear as possible, restrictions were included on studies reporting multiple correlations of similar variables. The variable chosen for reporting was based on a series of decision rules, specifically:

(1) When studies provided a correlation to gait velocity for both normalized and not normalized strength [35,48,52], only normalized strength was included in the figure, as normalized strength provides a better indication of an individual's strength, relative to their physical characteristics.
(2) When studies provided correlations between gait velocity and strength measured over multiple sessions [9,37], only the initial assessment was included in Figure 2.
(3) When studies provided strength measures at multiple knee joint angles [49], only the knee joint was included at 90° in the figure as the majority of studies used this joint angle.
(4) When studies included correlations of multiple measures of strength (e.g. force and torque) [35], only measures of force in Figure 2 were included.
(5) When studies included correlations between strength and both comfortable and fast paced gait [36,38,48], only fast paced gait was included in the figure as to only report one correlation for the same study.

Appendix G – Study Two manuscript

The results from Study Two have been published in *PLOS ONE* (Mentiplay et al., 2015b). This is an open access journal with a licence that allows for the manuscript to be downloaded, reused, reprinted, modified, distributed and/or copied. The publishers were contacted via email who confirmed that the full text could be provided in this thesis. The article can be found in the following pages or on the publisher's website at:

http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0140822

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RESEARCH ARTICLE

Assessment of Lower Limb Muscle Strength and Power Using Hand-Held and Fixed Dynamometry: A Reliability and Validity Study

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Abstract

Introduction

Hand-held dynamometry (HHD) has never previously been used to examine isometric muscle power. Rate of force development (RFD) is often used for muscle power assessment, however no consensus currently exists on the most appropriate method of calculation. The aim of this study was to examine the reliability of different algorithms for RFD calculation and to examine the intra-rater, inter-rater, and inter-device reliability of HHD as well as the concurrent validity of HHD for the assessment of isometric lower limb muscle strength and power.

Methods

30 healthy young adults (age: 23±5yrs, male: 15) were assessed on two sessions. Isometric muscle strength and power were measured using peak force and RFD respectively using two HHDs (Lafayette Model-01165 and Hoggan micro*FET*2) and a criterion-reference Kin-Com dynamometer. Statistical analysis of reliability and validity comprised intraclass correlation coefficients (ICC), Pearson correlations, concordance correlations, standard error of measurement, and minimal detectable change.

Results

Comparison of RFD methods revealed that a peak 200ms moving window algorithm provided optimal reliability results. Intra-rater, inter-rater, and inter-device reliability analysis of peak force and RFD revealed mostly good to excellent reliability (coefficients $\geq$ 0.70) for all

muscle groups. Concurrent validity analysis showed moderate to excellent relationships between HHD and fixed dynamometry for the hip and knee (ICCs $\geq$ 0.70) for both peak force and RFD, with mostly poor to good results shown for the ankle muscles (ICCs = 0.31–0.79).

Conclusions

Hand-held dynamometry has good to excellent reliability and validity for most measures of isometric lower limb strength and power in a healthy population, particularly for proximal muscle groups. To aid implementation we have created freely available software to extract these variables from data stored on the Lafayette device. Future research should examine the reliability and validity of these variables in clinical populations.

Introduction

Muscular weakness, as a component of muscle function, is an impairment that is commonly observed in clinical populations and has been widely documented to impact upon physical function [1–4]. Two important components of muscle function are the peak force that a muscle group can produce (muscle strength) and how rapidly that force can be produced (muscle power) [3, 5]. The latter has previously been quantified by calculating the rate of force development (RFD), which is calculated by measuring the change in force over a certain time period (Δforce/Δtime), usually during an isometric contraction [5, 6]. The measure of RFD has important functional implications; sufficient RFD is necessary to perform quick and forceful muscle contractions, such as those observed during walking [5]. Previous literature indicates that reduced muscle power, often associated with aging, may contribute to reduced physical function and an increased risk of falls in a range of clinical populations [7–13]. As such, assessments of muscle power may be useful in clinical settings for identifying individuals at risk of falls and functional limitations.

Currently there are varying methods utilised to calculate RFD from isometric contractions. Commonly used methods involve calculating the change in force over the change in time with discrete time intervals from the onset of contraction to 30, 50 or 100ms [5, 14, 15]. However, onset of contraction has been defined in different ways including when the force reading exceeds a set threshold of either absolute values or percentages of a maximal voluntary contraction [5, 14, 16–18]. Other methods of calculating RFD involve examining successive time intervals (e.g. 5ms) during the initial rise in force to determine the peak RFD across the trial [19–21], or examining the RFD between percentages of the peak force (e.g. between 30 and 60% of peak force) [22]. There is currently no consensus as to which measure of RFD should be used in the assessment of muscle power.

The criterion-reference assessment of muscle strength and power involves fixed laboratory-based dynamometry. A limitation of laboratory-based dynamometers is they are expensive and cumbersome which precludes their use as a clinically-feasible device for routine patient assessment [23–25]. Other devices that can be used to assess dynamic muscle power include linear position transducers [26–28], the Nottingham power rig [28–30], and force plates [31, 32], however the cost, availability, time-consuming nature, and difficulty of implementation of such assessments may limit their use in clinical settings. Clinic-based assessment of muscle power is important to allow widespread access to testing and easily-interpreted results. Commonly used devices that measure isometric lower limb muscle strength include hand-held

dynamometers (HHDs). These low-cost and portable devices are an appropriate and convenient method to assess muscle strength in a clinical setting due to their strong reliability and validity when compared with expensive laboratory-based dynamometers [23–25, 33, 34]. Previous psychometric literature assessing isometric lower limb strength using HHDs has focused predominantly on the knee extensors, with limited information on the validity of HHDs when assessing the muscle strength of other lower limb muscle groups [25, 34]. Additionally, the reliability and validity of HHDs for the assessment of isometric muscle power is currently unknown and warrants further investigation due to the importance of muscle power [30, 35].

The first aim of this study was to examine the reliability of different algorithms for assessment of RFD using fixed dynamometry. Secondly, this study aimed to determine the concurrent validity of two HHDs (Lafayette and Hoggan manufactured devices) compared to fixed dynamometry (KinCom) to assess isometric lower limb muscle strength and power using measures of peak force and RFD. Additionally, the intra-rater, inter-rater, and inter-device reliability of each device for the assessment of peak force and RFD was assessed. It was hypothesised that the HHDs would demonstrate good validity and reliability for the assessment of both muscle strength and power (intraclass correlation coefficients $\geq$0.75).

Materials and Methods

Participants

The isometric lower limb muscle strength and power of 30 healthy participants over the age of 18 was assessed. Participants were required to have no lower limb injury in the preceding two months or other comorbidities such as cardiovascular or respiratory conditions that could potentially impact on the assessment of muscle strength and power. This study used a concurrent validity, test-retest reliability design whereby participants attended two identical testing sessions. This study had approval from the Australian Catholic University Human Research Ethics Committee, where a convenience sample of participants were recruited. All participants gave written informed consent.

Instrumentation

Two HHDs were used to assess lower limb strength and power: a Lafayette Manual Muscle Testing System Model-01165 (Lafayette Instrument Company, Lafayette IN, USA) and a Hoggan micro*FET*2 (Hoggan Scientific, LLC, Salt Lake City UT, USA). The two HHDs were left as purchased from each manufacturer with no additional padding secured to the devices. The approximate retail cost of the Lafayette device is US$1,200, with the Hoggan device costing approximately US$1,095 (plus US$495 for the software package). For determination of the validity of each HHD, participants were also assessed using a fixed, laboratory-based KinCom dynamometer (Chattex Corporation, Chattanooga TN, USA). Laboratory-based dynamometers can often cost in excess of US$50,000. All devices recorded force in kilograms and were calibrated once at the start of the study. Both assessors were male and were experienced at using such devices, with Assessor-A having one year experience using HHDs and Assessor-B having 10 years of clinical physiotherapy experience using HHDs.

Procedure

Currently there is no consensus on the most appropriate testing positions for HHD use, with a recent systematic review demonstrating a variety of methodologies used for lower limb assessment in previous research [25]. Based on prior research and our own pilot work of assessments in a variety of different positions, we implemented those shown in Fig 1. These testing positions

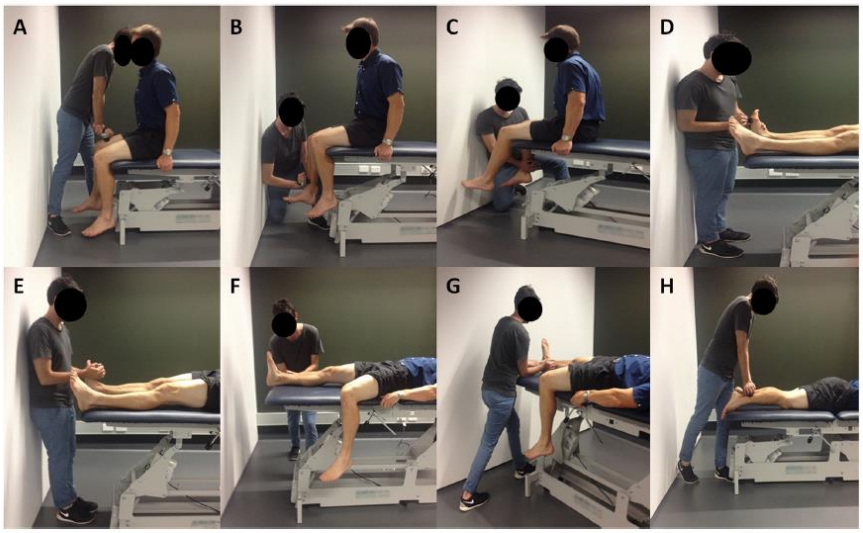

Fig 1. Testing positions for strength and power assessment. Note: Same positions were used on the fixed dynamometer. **(A)** Hip flexors with the participant seated and hips and knees flexed at 90°. Dynamometer placed on the anterior aspect of the thigh, proximal to the knee joint. **(B)** Knee extensors with the participant seated and hip and knees flexed at 90°. Dynamometer placed on the anterior aspect of the shank, proximal to the ankle joint. **(C)** Knee flexors with the participant seated and hips and knees flexed at 90°. Dynamometer placed on the posterior aspect of the shank, proximal to the ankle joint. **(D)** Ankle plantarflexors with the participant lying supine with the ankle in plantargrade and hips and knees extended. Dynamometer placed over the metatarsal heads on the sole of the foot. **(E)** Ankle dorsiflexors with the participant lying supine with the ankle relaxed and hips and knees extended. Dynamometer placed over the metatarsal heads on the dorsum of the foot. **(F)** Hip abductors with the participant lying supine and hips and knees extended. Dynamometer placed on the lateral aspect of the shank, proximal to the ankle joint. **(G)** Hip adductors with the participant lying supine and hips and knees extended. Dynamometer placed on the medial aspect of the shank, proximal to the ankle joint. **(H)** Hip extensors with the participant lying prone and hips and knees extended. Dynamometer placed on the posterior aspect of the shank, proximal to the ankle joint.

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have shown strong reliability for the measurement of isometric strength in previous studies for the hip [36], knee [37], and ankle [37] muscle groups.

Assessment of isometric muscle strength and power was performed with the participants in three positions (seated, supine, and prone); hip flexors, knee extensors, and knee flexors were assessed in a seated position; ankle plantarflexors, ankle dorsiflexors, hip abductors, and hip adductors in a supine position; hip extensors in a prone position. These positions were chosen to minimise changes in position by the participant to enhance the feasibility of testing in a clinical setting. All tests involved maximal voluntary isometric contractions. Assessment using the HHDs was conducted first. The order was randomised for assessor and HHD, however the order of the muscle groups tested was kept consistent as shown in Fig 1; for example if HHD1 was randomly assigned first, all seated muscle groups would be assessed, followed by HHD2 assessing seated muscle groups, with the same order of HHDs for supine and then prone muscle groups. Following a rest period of five minutes, the same protocol was repeated by the second assessor. During pilot testing, problems arose in the assessment of very strong muscle groups, namely the knee extensors and ankle plantarflexors. To assist the assessor in overcoming the force produced by the participant, the plinth was placed close to a wall, which aided the assessors in their resistance of the participants' contractions for these two muscle groups (see Fig 1B and 1D).

Following HHD testing, the isometric strength and power of participants was then assessed using the KinCom dynamometer utilising the positions described for the HHDs. In order to minimise position changes and reduce time requirements, the order of muscles tested was different during the assessment with the KinCom dynamometer. The order for the KinCom was as follows: knee extensors, knee flexors, hip flexors, hip abductors, hip adductors, hip extensors, ankle plantarflexors, and ankle dorsifexors. Instructions provided to participants for all trials were 'at the count of three, push/pull as hard and as fast as you can and hold that contraction until I say relax'. Each test lasted between three to five seconds and ended after a steady maximal force was produced by the participant. Participants were instructed to hold the side of the plinth for stabilization (see Fig 1). Constant verbal encouragement was provided throughout the testing. Only the right limb of each participant was assessed to reduce fatigue and the time demands of the testing session. A submaximal practice trial was given for each muscle group on both HHDs and the fixed dynamometer to ensure the participant understood the contraction required. Two trials were recorded for each muscle group, again to minimise the time requirements of testing.

Data Analysis

A custom-written software program (LabVIEW 2009 National Instruments, Austin TX, USA) was made to analyse the data from the three devices using the following procedures. A zero-phase shift 10Hz lowpass 4th order Butterworth filter was applied to data from each of the three devices. Due to the differing sampling rates between devices (Lafayette: stable 40Hz; Hoggan: unstable, approximately 100Hz; KinCom: stable 1000Hz), the data for the HHDs were resampled to a constant interval 1000Hz using cubic spline interpolation to allow for consistent and unbiased analysis. Strength was assessed by measuring peak force, which was determined by calculating the highest force value recorded in kilograms during both trials for each muscle group. Whilst normalisation to the length of the lever arm and body mass is crucial if comparing results from HHDs between participants, data from this study were not normalised in this way; our analysis of results was only performed within participants and therefore normalisation was redundant.

There is currently no consensus in the literature on the most appropriate measure of RFD [5, 19, 22]. Thus a comparison of the reliability of differing methodologies on the criterion-reference KinCom dynamometer was included in the current study. The analysis methods used included variants of three methods for the assessment of muscle power: 1) time to peak force, 2) calculating peak RFD between percentages of the peak force (5–95%, 10–90%, 15–85%, 20–80%, 25–75%, 30–70%, 35–65%, 40–60%), and, 3) examining successive time intervals (e.g. sample 1–11, 2–12, 3–13 etc.) during the initial rise in force to determine the peak RFD across the trial for time intervals of 10, 20, 50, 100, and 200ms. The methods differed in that the second method has a fixed position on the force trace but a variable time interval (i.e. it is always between the set force thresholds, but the duration shortens if the RFD is higher), whilst the third method has a fixed time interval but variable force position (i.e. the extracted data always has the same number of samples in it, but it could occur anywhere on the ascending slope of the force trace).

Statistical Analysis

Data were assessed for normality using a Shapiro-Wilk test, with the data conforming to normal distribution. Descriptive statistics (mean and standard deviations) were used to describe participant demographics and anthropometrics and outcome measures of peak force and RFD. The first step in analysis was to calculate the reliability of different RFD algorithms from the fixed dynamometer, which was done through intraclass correlation coefficients ($ICC_{2,1}$).

Assessment of intra-rater and inter-rater reliability was conducted using $ICC_{2,1}$, standard error of measurement (SEM), and minimal detectable change (MDC) with 95% confidence intervals. The SEM and MDC were calculated using the formulas provided by Portney and Watkins [38] and expressed as percentages of the mean. The SEM was calculated by multiplying the standard deviation of the first session results by the square root of one minus the ICC ($SEM = SD_1\sqrt{1 - ICC}$) [38]. The MDC was calculated using the following formula $MDC = z \times SEM \times \sqrt{2}$, where z = 1.96 (based on 95% confidence) and SEM is the standard error of measurement [38]. The association and agreement between assessors and devices, for inter-rater and inter-device reliability, were also measured using Pearson's correlation (R) and concordance correlation coefficients (R_c). The Pearson's correlation coefficient assesses association irrespective of magnitude differences whereas the concordance coefficient assesses both association and deviations from the line of identity (y = x).

Analysis of concurrent validity was conducted by comparing results from the two HHDs to the gold standard laboratory-based KinCom using $ICC_{2,1}$, R, and R_c. Standard or regression-based (when proportional bias was detected) Bland-Altman plots with 95% limits of agreement [39] were calculated for all variables (see S1–S4 Files). Correlations of the difference between scores and the average scores were examined to detect a proportional bias (R>0.50), which indicated use of a regression-based Bland-Altman plot. Point estimates of the correlation and ICC values for reliability and validity analyses were based on those provided by Portney and Watkins [38] interpreted as excellent (≥0.90), good (0.75–0.89), moderate (0.50–0.74), or poor (<0.50).

Results

A convenience sample of thirty participants (age: 22.87±5.08yrs, mass: 68.67±9.15kg, height: 172.85±9.11cm, male: 15) who were recruited through the University attended two testing sessions one week apart (mean: 7±2 days). One participant was unable to attend the second session. Further explanation of missing data is provided in S1–S4 Files and the full data set is in S5 File.

Reliability of RFD measures

Measures of time to peak force and RFD that involved calculating the change in force over the change in time between percentages of the peak force (5–95%, 10–90%, 15–85%, 20–80%, 25–75%, 30–70%, 35–65%, 40–60%) revealed poor to moderate test re-test reliability (median ICC<0.85) across the majority of muscle groups on the fixed KinCom dynamometer (Table 1). Examination of the RFD measures calculated across successive time intervals (10, 20, 50, 100, and 200ms) showed good to excellent results for test re-test reliability on the KinCom dynamometer (median ICC≥0.91). The 200ms time interval method displayed the highest median reliability results (median ICC = 0.93) and no results lower than our threshold for good (≥0.75), and was therefore used for further analyses.

Intra- and Inter-rater Reliability

The mean (standard deviation (SD)) and intra-rater reliability results for peak force and RFD are shown in Tables 2 and 3 respectively. Intra-rater reliability was good to excellent (ICC≥0.75) for all peak force measures with the exception of a moderate result for the ankle plantarflexors measured by Assessor-B using the Hoggan device (ICC = 0.74). Intra-rater reliability was also good to excellent for all RFD measures with the exception of the knee extensors measured by Assessor-A using the Hoggan device (ICC = 0.71), and measures of ankle

Table 1. Test-retest reliability (ICCs) of different rate of force development measures on the fixed KinCom dynamometer.

Musclegroups	Time to peak	Percentage of peak force measures								Successive time intervals				
		RFD (5–95)	RFD (10–90)	RFD (15–85)	RFD (20–80)	RFD (25–75)	RFD (30–70)	RFD (35–65)	RFD (40–60)	Peak RFD (10ms)	Peak RFD (20ms)	Peak RFD (50ms)	Peak RFD (100ms)	Peak RFD (200ms)
ADF	-0.93	0.24	0.49	0.71	0.7	0.65	0.63	0.63	0.62	0.64	0.65	0.62	0.72	0.77
APF	0.67	0.95	0.96	0.97	0.95	0.87	0.85	0.88	0.88	0.96	0.96	0.96	0.95	0.95
HAB	-0.47	-0.22	0.45	0.59	0.77	0.82	0.81	0.79	0.83	0.83	0.83	0.86	0.9	0.88
HAD	0.46	0.47	0.62	0.56	0.59	0.75	0.74	0.77	0.77	0.78	0.79	0.8	0.88	0.92
HE	0.40	0.41	0.17	0.26	0.54	0.57	0.84	0.79	0.85	0.91	0.91	0.91	0.91	0.87
HF	0.70	0.77	0.92	0.94	0.95	0.95	0.94	0.94	0.94	0.95	0.95	0.95	0.95	0.94
KE	0.75	0.82	0.83	0.91	0.91	0.92	0.91	0.9	0.9	0.97	0.97	0.97	0.97	0.98
KF	0.39	0.77	0.84	0.78	0.73	0.7	0.66	0.66	0.67	0.93	0.93	0.92	0.89	0.93
Median	0.43	0.62	0.73	0.75	0.75	0.79	0.83	0.79	0.84	0.92	0.92	0.92	0.91	0.93
IQR	0.18–0.68	0.37–0.78	0.48–0.86	0.58–0.92	0.67–0.92	0.69–0.88	0.72–0.87	0.74–0.89	0.75–0.89	0.82–0.95	0.82–0.95	0.85–0.95	0.89–0.95	0.88–0.94
N = <0.75	7	4	4	4	4	3	3	2	2	1	1	1	1	0

Abbreviations: RFD: rate of force development; ADF: ankle dorsiflexors; APF: ankle plantarflexors; HAB: hip abductors; HAD: hip adductors; HE: hip extensors; HF: hip flexors; KE: knee extensors; KF: knee flexors; IQR: interquartile range (25–75%); N = <0.75: number of muscle groups below the threshold of 0.75.

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dorsiflexors (ICC = 0.49), hip abductors (ICC = 0.74), and knee extensors (ICC = 0.71) using the Lafayette device by Assessor-B.

Inter-rater reliability results are displayed in Table 4. Inter-rater reliability was good to excellent for both peak force and RFD measures (ICC≥0.75) in all muscle groups except for peak force of the ankle dorsiflexors (ICC = 0.68) and ankle plantarflexors (ICC = 0.66) measured on the Hoggan device, and RFD of the ankle dorsiflexors measured on the Lafayette device (ICC = 0.70). The tables also show the intra- and inter-rater reliability results of the SEM and MDC calculations, expressed as a percentage of the mean.

Inter-device Reliability

Analysis of inter-device results showed good to excellent correlations (R≥0.75) between results obtained on the Lafayette and Hoggan devices for all peak force measures (Table 4). Additionally, concordance correlations for peak force also showed good to excellent agreement (R_c≥0.75) with the exception of ankle dorsiflexors (R_c = 0.66) measured by Assessor-A. Inter-device analysis of RFD measures showed good to excellent correlations (R≥0.75) for all muscle groups with the exception of the ankle dorsiflexors measured by Assessor-B (R = 0.73) and the knee extensors for Assessors-A and B (R = 0.41, 0.57 respectively). The majority of RFD concordance correlation results showed moderate to good agreement (see Table 4). Measures of RFD for the knee extensors showed poor agreement and moderate correlations between devices for both assessors.

Concurrent Validity

Results from the validity analysis for peak force and RFD measures are shown in Table 5. Validity of peak force measures were good to excellent (ICC≥0.75) with the exception of most ankle results which demonstrated moderate validity; this included ankle dorsiflexors measured by Assessor-A on the Lafayette device (ICC = 0.62) and the Hoggan device (ICC = 0.51) and

Table 2. Mean (SD) values and intra-rater reliability for each assessor on each device plus the KinCom for peak force (kg).

Muscle Groups	Intra-rater reliability	Assessor-A		Assessor-B		KinCom
		Lafayette	Hoggan	Lafayette	Hoggan	
ADF	Day 1—Mean (SD)	19.19 (4.92)	20.89 (3.64)	27.47 (5.96)	30.68 (6.89)	18.47 (6.87)
	Day 2—Mean (SD)	17.83 (4.35)	20.92 (4.11)	27.42 (5.85)	29.93 (5.49)	17.52 (6.30)
	ICC (95% CI)	0.89 (0.76,0.95)	0.87 (0.71,0.94)	0.88 (0.75,0.95)	0.87 (0.71,0.94)	0.78 (0.43,0.92)
	SEM (%)	8.62	6.20	7.39	8.13	17.45
	MDC (%)	23.89	17.19	20.47	22.52	48.36
APF	Day 1—Mean (SD)	51.00 (10.94)	48.06 (8.12)	52.29 (11.17)	51.16 (10.85)	91.02 (35.94)
	Day 2—Mean (SD)	50.42 (11.34)	47.83 (9.70)	51.95 (10.05)	51.30 (11.27)	83.16 (36.13)
	ICC (95% CI)	0.84 (0.66,0.93)	0.87 (0.70,0.95)	0.87 (0.72,0.94)	0.74 (0.38,0.89)	0.98 (0.95,0.99)
	SEM (%)	8.53	6.06	7.70	10.81	5.72
	MDC (%)	23.64	16.81	21.35	29.97	15.86
HAB	Day 1—Mean (SD)	13.85 (3.73)	13.23 (3.91)	13.06 (3.03)	13.38 (3.83)	11.91 (3.39)
	Day 2—Mean (SD)	13.01 (3.27)	12.77 (3.50)	12.46 (3.71	12.94 (3.74)	11.14 (3.45)
	ICC (95% CI)	0.87 (0.73,0.94)	0.94 (0.86,0.97)	0.92 (0.84,0.96)	0.95 (0.89,0.98)	0.95 (0.88,0.98)
	SEM (%)	9.59	7.30	6.43	6.53	6.17
	MDC (%)	26.59	20.23	17.82	18.11	17.10
HAD	Day 1—Mean (SD)	18.27 (6.31)	17.53 (5.81)	19.65 (6.91)	20.37 (7.27)	19.56 (5.91)
	Day 2—Mean (SD)	18.57 (6.27)	18.16 (5.84)	19.10 (7.45)	19.56 (6.99)	18.92 (6.81)
	ICC (95% CI)	0.96 (0.92,0.98)	0.97 (0.92,0.99)	0.97 (0.93,0.99)	0.97 (0.92,0.99)	0.98 (0.94–0.99)
	SEM (%)	6.82	5.74	6.09	6.68	4.48
	MDC (%)	18.89	15.91	16.87	18.51	12.42
HE	Day 1—Mean (SD)	23.01 (5.34)	23.60 (5.69)	25.25 (6.80)	24.41 (5.66)	25.82 (6.58)
	Day 2—Mean (SD)	23.45 (6.62)	23.34 (5.92)	25.16 (6.67)	24.31 (5.97)	25.43 (7.13)
	ICC (95% CI)	0.92 (0.82,0.96)	0.95 (0.90,0.98)	0.94 (0.86,0.97)	0.95 (0.88,0.98)	0.92 (0.81,0.97)
	SEM (%)	6.77	5.22	6.76	5.34	7.03
	MDC (%)	18.76	14.48	18.74	14.79	19.49
HF	Day 1—Mean (SD)	30.44 (7.84)	31.23 (7.82)	36.54 (8.23)	38.63 (8.26)	34.83 (10.48)
	Day 2—Mean (SD)	30.05 (6.53)	31.72 (7.81)	36.62 (6.74)	36.53 (7.50)	35.86 (9.73)
	ICC (95% CI)	0.94 (0.88,0.97)	0.95 (0.89,0.98)	0.93 (0.86,0.97)	0.85 (0.67,0.94)	0.95 (0.89,0.98)
	SEM (%)	6.15	5.43	5.83	8.17	6.45
	MDC (%)	17.05	15.05	16.16	22.65	17.89
KE	Day 1—Mean (SD)	44.27 (11.34)	50.41 (13.89)	43.92 (13.62)	47.70 (13.03)	63.54 (23.76)
	Day 2—Mean (SD)	41.51 (11.55)	46.07 (12.49)	42.66 (13.52)	46.13 (13.86)	58.66 (25.19)
	ICC (95% CI)	0.91 (0.80,0.96)	0.90 (0.76,0.96)	0.92 (0.83,0.96)	0.89 (0.76,0.95)	0.98 (0.94,0.99)
	SEM (%)	7.73	8.54	8.72	8.98	5.67
	MDC (%)	21.42	23.67	24.16	24.88	15.72
KF	Day 1—Mean (SD)	23.28 (5.74)	23.58 (6.19)	27.55 (9.15)	29.46 (7.69)	25.84 (7.28)
	Day 2—Mean (SD)	23.19 (5.25)	23.99 (4.84)	27.49 (7.90)	28.67 (7.45)	25.73 (7.35)
	ICC (95% CI)	0.92 (0.83,0.96)	0.89 (0.71,0.96)	0.94 (0.87,0.97)	0.96 (0.90,0.98)	0.94 (0.86,0.98)
	SEM (%)	6.93	8.59	8.07	5.29	6.67
	MDC (%)	19.21	23.81	22.36	14.66	18.48

Abbreviations: ADF: ankle dorsiflexors; APF: ankle plantarflexors; HAB: hip abductors; HAD: hip adductors; HE: hip extensors; HF: hip flexors; KE: knee extensors; KF: knee flexors; SD: standard deviation; CI: confidence intervals; SEM: standard error measurement (expressed as a percentage of the mean); MDC: minimal detectable change with 95% confidence intervals (expressed as a percentage of the mean). A description of missing data is outlined in S1–S4 Files.

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Table 3. Mean (SD) values and intra-rater reliability for each assessor on each device plus the KinCom for rate of force development (kg/s).

Muscle Groups	Intra-rater reliability	Assessor-A		Assessor-B		KinCom
		Lafayette	Hoggan	Lafayette	Hoggan	
ADF	Day 1—Mean (SD)	35.55 (11.38)	46.17 (12.51)	53.06 (14.63)	71.28 (18.92)	67.74 (28.40)
	Day 2—Mean (SD)	32.90 (10.27)	45.46 (13.73)	53.34 (17.96)	68.26 (19.70)	64.59 (25.61)
	ICC (95% CI)	0.87 (0.72,0.94)	0.84 (0.63,0.93)	0.49 (-0.10,0.76)	0.75 (0.44,0.88)	0.77 (0.40,0.91)
	SEM (%)	11.63	11.01	19.69	13.38	20.24
	MDC (%)	32.24	30.52	54.57	37.09	56.10
APF	Day 1—Mean (SD)	111.31 (35.70)	125.40 (35.58)	118.54 (38.41)	144.89 (40.28)	230.81 (113.89)
	Day 2—Mean (SD)	107.63 (27.01)	119.24 (35.82)	113.41 (27.76)	143.09 (41.15)	216.40 (111.54)
	ICC (95% CI)	0.89 (0.76,0.95)	0.81 (0.55,0.92)	0.85 (0.67,0.93)	0.81 (0.56,0.92)	0.95 (0.88,0.98)
	SEM (%)	10.64	12.37	12.68	12.05	10.81
	MDC (%)	29.48	34.28	35.14	33.41	29.96
HAB	Day 1—Mean (SD)	30.49 (10.01)	34.80 (13.56)	30.08 (9.19)	37.78 (15.86)	37.75 (15.12)
	Day 2—Mean (SD)	28.80 (7.54)	33.51 (9.30)	29.16 (8.30)	36.71 (13.45)	34.35 (13.64)
	ICC (95% CI)	0.84 (0.66,0.93)	0.90 (0.77,0.95)	0.74 (0.44,0.88)	0.89 (0.76,0.95)	0.88 (0.71,0.95)
	SEM (%)	13.08	12.50	15.69	13.92	13.65
	MDC (%)	36.27	34.65	43.49	38.59	37.83
HAD	Day 1—Mean (SD)	39.97 (17.13)	43.42 (19.90)	44.73 (19.67)	58.55 (27.95)	58.23 (24.36)
	Day 2—Mean (SD)	39.33 (13.02)	46.55 (14.52)	43.54 (16.15)	55.74 (22.40)	54.76 (27.89)
	ICC (95% CI)	0.91 (0.80,0.96)	0.87 (0.64,0.95)	0.93 (0.84,0.97)	0.94 (0.86,0.98)	0.92 (0.78,0.97)
	SEM (%)	13.00	16.85	11.96	11.69	12.13
	MDC (%)	36.04	46.69	33.15	32.40	33.61
HE	Day 1—Mean (SD)	47.42 (15.08)	56.88 (20.79)	58.21 (17.55)	72.18 (25.61)	83.10 (29.19)
	Day 2—Mean (SD)	48.26 (14.57)	56.31 (14.84)	55.82 (15.43)	67.79 (17.93)	84.39 (28.50)
	ICC (95% CI)	0.91 (0.80,0.96)	0.86 (0.69,0.94)	0.87 (0.73,0.94)	0.89 (0.74,0.95)	0.87 (0.68,0.95)
	SEM (%)	9.70	13.58	10.71	11.82	12.62
	MDC (%)	26.88	37.64	29.67	32.77	34.98
HF	Day 1—Mean (SD)	67.45 (18.88)	88.05 (23.72)	84.78 (23.54)	112.95 (30.30)	147.38 (46.94)
	Day 2—Mean (SD)	65.82 (17.32)	89.84 (22.51)	82.34 (18.84)	104.49 (28.15)	152.80 (54.08)
	ICC (95% CI)	0.88 (0.75,0.94)	0.86 (0.66,0.94)	0.82 (0.62,0.92)	0.87 (0.71,0.95)	0.94 (0.85,0.98)
	SEM (%)	9.65	10.26	11.68	9.52	7.87
	MDC (%)	26.76	28.43	32.38	26.39	21.80
KE	Day 1—Mean (SD)	83.24 (27.78)	126.25 (55.88)	87.65 (24.45)	125.37 (43.44)	210.61 (91.22)
	Day 2—Mean (SD)	82.36 (27.09)	106.23 (34.03)	80.38 (25.90)	112.72 (36.38)	200.01 (86.90)
	ICC (95% CI)	0.84 (0.66,0.93)	0.71 (0.26,0.88)	0.71 (0.37,0.87)	0.77 (0.50,0.90)	0.98 (0.95,0.99)
	SEM (%)	13.18	24.04	15.02	16.55	5.81
	MDC (%)	36.54	66.63	41.64	45.86	16.11
KF	Day 1—Mean (SD)	42.87 (16.77)	52.07 (17.22)	53.92 (24.01)	77.15 (27.58)	90.55 (28.42)
	Day 2—Mean (SD)	38.86 (13.53)	49.83 (16.10)	52.47 (15.47)	70.63 (20.90)	92.74 (36.16)
	ICC (95% CI)	0.91 (0.80,0.96)	0.78 (0.38,0.92)	0.85 (0.69,0.93)	0.83 (0.56,0.94)	0.93 (0.82,0.97)
	SEM (%)	11.99	15.65	17.02	14.69	8.48
	MDC (%)	33.24	43.38	47.17	40.73	23.51

Abbreviations: ADF: ankle dorsiflexors; APF: ankle plantarflexors; HAB: hip abductors; HAD: hip adductors; HE: hip extensors; HF: hip flexors; KE: knee extensors; KF: knee flexors; SD: standard deviation; ICC: intraclass correlation coefficient; CI: confidence intervals; SEM: standard error measurement (expressed as a percentage of the mean); MDC: minimal detectable change with 95% confidence intervals (expressed as a percentage of the mean). A description of missing data is outlined in S1–S4 Files.

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Table 4. Inter-rater and inter-device reliability for the HHDs.

Muscle Groups		Inter-rater reliability				Inter-device reliability			
		Peak Force (kg)		RFD (kg/s)		Peak Force (kg)		RFD (kg/s)	
		Lafayette	Hoggan	Lafayette	Hoggan	Assessor-A	Assessor-B	Assessor-A	Assessor-B
ADF	ICC (95% CI)	0.77 (0.50,0.89)	0.68 (0.29,0.86)	0.70 (0.36,0.86)	0.75 (0.44,0.89)				
	SEM (%)	11.30	11.54	16.05	13.41				
	MDC (%)	22.15	22.63	31.46	26.28				
	R (95% CI)	0.59 (0.29,0.79)	0.61 (0.29,0.81)	0.52 (0.19,0.74)	0.68 (0.40,0.84)	0.79 (0.59,0.90)	0.84 (0.68,0.92)	0.85 (0.70,0.93)	0.73 (0.49,0.87)
	R_c (95% CI)	0.25 (0.09,0.40)	0.19 (0.06,0.32)	0.24 (0.06,0.41)	0.26 (0.10,0.40)	0.66 (0.44,0.81)	0.76 (0.57,0.87)	0.53 (0.34,0.68)	0.44 (0.23,0.61)
APF	ICC (95% CI)	0.81 (0.60,0.91)	0.66 (0.24,0.85)	0.90 (0.79,0.95)	0.83 (0.61,0.92)				
	SEM (%)	9.33	11.18	10.25	11.74				
	MDC (%)	18.29	21.91	20.08	23.01				
	R (95% CI)	0.66 (0.39,0.83)	0.47 (0.10,0.73)	0.78 (0.58,0.89)	0.71 (0.45,0.86)	0.85 (0.70,0.93)	0.75 (0.52,0.88)	0.86 (0.71,0.93)	0.78 (0.57,0.89)
	R_c (95% CI)	0.66 (0.40,0.83)	0.44 (0.10,0.69)	0.77 (0.56,0.88)	0.66 (0.40,0.82)	0.80 (0.64,0.89)	0.75 (0.52,0.88)	0.74 (0.55,0.85)	0.61 (0.39,0.77)
HAB	ICC (95% CI)	0.92 (0.84,0.96)	0.95 (0.89,0.98)	0.92 (0.82,0.96)	0.88 (0.73,0.94)				
	SEM (%)	6.92	6.51	9.24	14.27				
	MDC (%)	13.56	12.75	18.10	27.97				
	R (95% CI)	0.89 (0.78,0.95)	0.91 (0.81,0.96)	0.85 (0.71,0.93)	0.80 (0.61,0.90)	0.96 (0.92,0.98)	0.92 (0.83,0.96)	0.90 (0.79,0.95)	0.84 (0.69,0.92)
	R_c (95% CI)	0.84 (0.71,0.91)	0.91 (0.82,0.96)	0.85 (0.71,0.92)	0.78 (0.59,0.88)	0.96 (0.91,0.98)	0.89 (0.81,0.94)	0.80 (0.65,0.88)	0.64 (0.47,0.77)
HAD	ICC (95% CI)	0.98 (0.96,0.99)	0.95 (0.88,0.98)	0.92 (0.82,0.96)	0.91 (0.79,0.96)				
	SEM (%)	4.54	7.72	12.59	14.00				
	MDC (%)	8.90	15.12	24.68	27.44				
	R (95% CI)	0.96 (0.92,0.98)	0.92 (0.82,0.97)	0.82 (0.64,0.91)	0.84 (0.66,0.93)	0.95 (0.89,0.98)	0.96 (0.91,0.98)	0.84 (0.66,0.93)	0.91 (0.81,0.96)
	R_c (95% CI)	0.94 (0.88,0.97)	0.86 (0.73,0.93)	0.77 (0.59,0.88)	0.71 (0.50,0.84)	0.95 (0.88,0.98)	0.96 (0.91,0.98)	0.71 (0.53,0.83)	0.73 (0.56,0.84)
HE	ICC (95% CI)	0.92 (0.82,0.96)	0.95 (0.89,0.98)	0.89 (0.77,0.95)	0.86 (0.70,0.94)				
	SEM (%)	7.29	5.34	10.15	13.36				
	MDC (%)	14.29	10.46	19.90	26.18				
	R (95% CI)	0.87 (0.74,0.94)	0.90 (0.79,0.95)	0.83 (0.67,0.92)	0.79 (0.59,0.90)	0.96 (0.92,0.98)	0.93 (0.85,0.97)	0.77 (0.56,0.89)	0.89 (0.77,0.95)
	R_c (95% CI)	0.78 (0.63,0.88)	0.89 (0.77,0.95)	0.64 (0.44,0.78)	0.61 (0.39,0.76)	0.95 (0.89,0.98)	0.89 (0.79,0.94)	0.64 (0.42,0.78)	0.70 (0.52,0.82)
HF	ICC (95% CI)	0.93 (0.85,0.97)	0.92 (0.80,0.96)	0.85 (0.69,0.93)	0.87 (0.69,0.94)				
	SEM (%)	6.39	6.71	10.76	9.80				
	MDC (%)	12.53	13.15	21.08	19.21				
	R (95% CI)	0.86 (0.73,0.93)	0.84 (0.66,0.93)	0.83 (0.67,0.92)	0.75 (0.49,0.89)	0.91 (0.80,0.96)	0.82 (0.64,0.91)	0.85 (0.69,0.93)	0.81 (0.62,0.91)
	R_c (95% CI)	0.69 (0.50,0.81)	0.63 (0.41,0.79)	0.61 (0.42,0.75)	0.57 (0.32,0.75)	0.91 (0.81,0.96)	0.81 (0.62,0.91)	0.54 (0.34,0.69)	0.56 (0.35,0.71)

(*Continued*)

Table 4. (*Continued*)

Muscle Groups		Inter-rater reliability				Inter-device reliability			
		Peak Force (kg)		RFD (kg/s)		Peak Force (kg)		RFD (kg/s)	
		Lafayette	Hoggan	Lafayette	Hoggan	Assessor-A	Assessor-B	Assessor-A	Assessor-B
KE	ICC (95% CI)	0.89 (0.77,0.95)	0.90 (0.77,0.96)	0.80 (0.56,0.91)	0.75 (0.44,0.89)				
	SEM (%)	9.30	8.76	13.84	19.58				
	MDC (%)	18.23	17.18	27.12	38.37				
	R (95% CI)	0.86 (0.71,0.93)	0.82 (0.63,0.92)	0.61 (0.31,0.80)	0.56 (0.21,0.78)	0.93 (0.85,0.97)	0.89 (0.77,0.95)	0.41 (0.02,0.69)	0.57 (0.25,0.78)
	R_c (95% CI)	0.84 (0.70,0.92)	0.81 (0.62,0.91)	0.60 (0.30,0.79)	0.54 (0.22,0.75)	0.83 (0.70,0.91)	0.85 (0.72,0.93)	0.24 (0.02,0.44)	0.31 (0.11,0.49)
KF	ICC (95% CI)	0.82 (0.62,0.91)	0.92 (0.77,0.97)	0.81 (0.60,0.91)	0.82 (0.49,0.94)				
	SEM (%)	12.53	7.40	18.46	14.71				
	MDC (%)	24.56	14.51	36.18	28.83				
	R (95% CI)	0.78 (0.58,0.89)	0.84 (0.59,0.94)	0.69 (0.44,0.84)	0.71 (0.33.0.89)	0.95 (0.88,0.98)	0.85 (0.68,0.93)	0.90 (0.76,0.96)	0.88 (0.74,0.95)
	R_c (95% CI)	0.61 (0.41,0.76)	0.70 (0.39,0.87)	0.55 (0.32,0.72)	0.43 (0.13,0.65)	0.94 (0.85,0.97)	0.84 (0.67,0.92)	0.78 (0.58,0.89)	0.66 (0.46,0.80)

Abbreviations: RFD: rate of force development; ADF: ankle dorsiflexors; APF: ankle plantarflexors; HAB: hip abductors; HAD: hip adductors; HE: hip extensors; HF: hip flexors; KE: knee extensors; KF: knee flexors; ICC: intraclass correlation coefficient; CI: confidence intervals; SEM: standard error measurement (expressed as a percentage of the mean); MDC: minimal detectable change with 95% confidence intervals (expressed as a percentage of the mean); R: Pearson's correlation coefficient; R_c: concordance correlation coefficient. A description of missing data is outlined in S1–S4 Files.

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ankle plantarflexors measured by Assessor-A and B on the Lafayette device (ICC = 0.51, 0.54 respectively) and the Hoggan device (ICC = 0.47, 0.40 respectively). The validity of RFD measures were mixed, however all measures of the hip musculature demonstrated good to excellent validity (ICC≥0.75) except for the hip abductors measured by Assessor-B using the Lafayette device (ICC = 0.74). Ankle and knee RFD measures displayed mostly moderate to good validity. Results from the Bland-Altman plots are provided in S1–S4 Files.

Discussion

Hand-held dynamometry demonstrated good to excellent intra- and inter-rater reliability for the assessment of isometric lower limb muscle strength and power in a healthy population. Comparison of the HHDs to a laboratory-based dynamometer showed moderate to excellent concurrent validity for both measures of isometric lower limb strength and power. To the authors' knowledge, this is the first study to evaluate the intra- and inter-rater reliability and validity of HHDs for assessing muscle strength in all major muscles of the lower limbs with a greater than poor sample size based on the COSMIN checklist [40], and the first to use HHDs to assess muscle power. These low-cost, portable, and easy-to-use devices have previously shown excellent results for use as a clinically-feasible alternative to laboratory-based dynamometry for the assessment of isometric muscle strength. The results from the current study indicate promise for HHDs in the assessment of isometric muscle power.

Previous literature has focussed primarily on the assessment and treatment of muscle strength in various clinical populations; however, muscle power is another important consideration. Evidence indicates that in an elderly population, measures of muscle power are more

Table 5. Concurrent validity analysis of the HHDs for assessment of peak force and RFD measures compared to the KinCom.

Muscle Groups	Validity	Peak Force (kg)				RFD (kg/s)			
		Assessor-A		Assessor-B		Assessor-A		Assessor-B	
		Lafayette	Hoggan	Lafayette	Hoggan	Lafayette	Hoggan	Lafayette	Hoggan
ADF	ICC (95% CI)	0.62 (0.15,0.83)	0.61 (0.09,0.83)	0.79 (0.52,0.91)	0.76 (0.44,0.90)	0.41 (-0.32,0.74)	0.40 (-0.36,0.74)	0.31 (-0.56,0.70)	0.72 (0.35,0.88)
	R (95% CI)	0.46 (0.09,0.72)	0.49 (0.11,0.75)	0.66 (0.36,0.84)	0.61 (0.28,0.81)	0.35 (-0.04,0.65)	0.34 (-0.06,0.65)	0.23 (-0.18,0.57)	0.60 (0.27,0.80)
	R_c (95% CI)	0.44 (0.10,0.70)	0.39 (0.09,0.63)	0.30 (0.11,0.46)	0.22 (0.06,0.36)	0.11 (-0.02,0.24)	0.17 (-0.04,0.36)	0.16 (-0.12,0.41)	0.54 (0.24,0.75)
APF	ICC (95% CI)	0.51 (-0.12,0.78)	0.47 (-0.25,0.78)	0.54 (-0.14,0.81)	0.40 (-0.42,0.74)	0.73 (0.38,0.88)	0.70 (0.31,0.87)	0.70 (0.32,0.87)	0.54 (-0.06,0.80)
	R (95% CI)	0.49 (0.12,0.74)	0.59 (0.24,0.81)	0.51 (0.14,0.75)	0.41 (0.00,0.70)	0.73 (0.47,0.87)	0.69 (0.40,0.86)	0.67 (0.37,0.84)	0.44 (0.05,0.72)
	R_c (95% CI)	0.16 (0.02,0.30)	0.13 (0.03,0.23)	0.17 (0.03,0.30)	0.11 (-0.01,0.22)	0.24 (0.10,0.38)	0.30 (0.12,0.46)	0.25 (0.09,0.39)	0.23 (0.01,0.43)
HAB	ICC (95% CI)	0.88 (0.74,0.95)	0.89 (0.75,0.95)	0.91 (0.80,0.96)	0.91 (0.79,0.96)	0.82 (0.60,0.92)	0.82 (0.59,0.92)	0.74 (0.42,0.88)	0.88 (0.74,0.95)
	R (95% CI)	0.79 (0.58,0.90)	0.80 (0.59,0.91)	0.85 (0.69,0.93)	0.83 (0.65,0.92)	0.76 (0.53,0.89)	0.70 (0.42,0.86)	0.66 (0.37,0.83)	0.79 (0.58,0.90)
	R_c (95% CI)	0.66 (0.43,0.81)	0.75 (0.52,0.88)	0.80 (0.63,0.90)	0.77 (0.57,0.89)	0.63 (0.40,0.78)	0.70 (0.43,0.85)	0.52 (0.26,0.70)	0.79 (0.59,0.90)
HAD	ICC (95% CI)	0.95 (0.87,0.98)	0.94 (0.84,0.98)	0.95 (0.89,0.98)	0.94 (0.85,0.98)	0.86 (0.68,0.94)	0.92 (0.80,0.97)	0.92 (0.82,0.97)	0.94 (0.87,0.98)
	R (95% CI)	0.90 (0.78,0.96)	0.90 (0.76,0.96)	0.91 (0.80,0.96)	0.89 (0.75,0.95)	0.82 (0.62,0.92)	0.87 (0.70,0.95)	0.88 (0.74,0.95)	0.90 (0.78,0.96)
	R_c (95% CI)	0.89 (0.76,0.95)	0.85 (0.67,0.93)	0.91 (0.80,0.96)	0.89 (0.76,0.95)	0.58 (0.36,0.74)	0.79 (0.57,0.90)	0.74 (0.55,0.86)	0.89 (0.76,0.95)
HE	ICC (95% CI)	0.88 (0.72,0.95)	0.90 (0.76,0.95)	0.94 (0.85,0.97)	0.93 (0.85,0.97)	0.76 (0.46,0.90)	0.88 (0.73,0.95)	0.87 (0.69,0.94)	0.88 (0.72,0.95)
	R (95% CI)	0.80 (0.59,0.91)	0.82 (0.62,0.92)	0.88 (0.74,0.95)	0.89 (0.76,0.95)	0.76 (0.52,0.89)	0.84 (0.67,0.93)	0.83 (0.65,0.92)	0.80 (0.59,0.91)
	R_c (95% CI)	0.72 (0.49,0.85)	0.77 (0.57,0.89)	0.88 (0.74,0.94)	0.86 (0.71,0.93)	0.28 (0.13,0.42)	0.52 (0.32,0.68)	0.52 (0.31,0.67)	0.74 (0.51,0.87)
HF	ICC (95% CI)	0.94 (0.87,0.97)	0.94 (0.85,0.97)	0.94 (0.86,0.97)	0.92 (0.82,0.97)	0.77 (0.50,0.90)	0.78 (0.49,0.91)	0.80 (0.56,0.91)	0.92 (0.82,0.97)
	R (95% CI)	0.92 (0.83,0.96)	0.90 (0.77,0.96)	0.90 (0.79,0.95)	0.88 (0.74,0.95)	0.88 (0.75,0.95)	0.77 (0.53,0.90)	0.79 (0.58,0.90)	0.95 (0.89,0.98)
	R_c (95% CI)	0.80 (0.65,0.89)	0.84 (0.68,0.92)	0.87 (0.76,0.93)	0.81 (0.64,0.91)	0.19 (0.09,0.28)	0.30 (0.13,0.45)	0.28 (0.14,0.42)	0.61 (0.44,0.74)
KE	ICC (95% CI)	0.82 (0.58,0.92)	0.90 (0.76,0.96)	0.92 (0.82,0.97)	0.88 (0.72,0.95)	0.40 (-0.37,0.74)	0.82 (0.58,0.92)	0.63 (0.16,0.84)	0.67 (0.24,0.85)
	R (95% CI)	0.82 (0.63,0.92)	0.87 (0.71,0.94)	0.90 (0.78,0.96)	0.86 (0.70,0.94)	0.36 (-0.04,0.66)	0.72 (0.45,0.87)	0.68 (0.39,0.85)	0.57 (0.23,0.79)
	R_c (95% CI)	0.48 (0.28,0.64)	0.71 (0.51,0.84)	0.61 (0.42,0.75)	0.62 (0.42,0.77)	0.07 (-0.01,0.15)	0.38 (0.17,0.56)	0.13 (0.04,0.22)	0.25 (0.07,0.41)
KF	ICC (95% CI)	0.80 (0.55,0.91)	0.79 (0.39,0.93)	0.85 (0.67,0.93)	0.87 (0.66,0.95)	0.72 (0.38,0.88)	0.79 (0.41,0.92)	0.84 (0.64,0.93)	0.84 (0.60,0.93)
	R (95% CI)	0.68 (0.40,0.84)	0.66 (0.25,0.87)	0.76 (0.53,0.89)	0.76 (0.48,0.90)	0.65 (0.35,0.83)	0.73 (0.39,0.90)	0.73 (0.48,0.87)	0.72 (0.42,0.88)
	R_c (95% CI)	0.64 (0.37,0.81)	0.65 (0.25,0.86)	0.72 (0.49,0.85)	0.73 (0.44,0.88)	0.18 (0.06,0.30)	0.29 (0.09,0.48)	0.36 (0.17,0.52)	0.58 (0.29,0.77)

Abbreviations: RFD: rate of force development; ADF: ankle dorsiflexors; APF: ankle plantarflexors; HAB: hip abductors; HAD: hip adductors; HE: hip extensors; HF: hip flexors; KE: knee extensors; KF: knee flexors; ICC: intraclass correlation coefficient; CI: confidence intervals; R: Pearson's correlation coefficient; R_c: concordance correlation coefficient. A description of missing data is outlined in S1–S4 Files.

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strongly associated with self-reported function and incidence of falls than muscle strength [30, 35]. As such, knowledge of both muscle strength and power may be of use to clinicians when assessing and treating their patients. The HHD results for both peak force and RFD can be obtained from the same trial using the same methodology, adding to the feasibility of using this device in a clinical setting for patient assessment. A potential limiting factor is the lack of widely available software to extract the RFD data. For this reason we have created a freely available software program (available at http://www.instrumentedmovement.com) which allows the user to obtain the 200ms rolling window RFD from data stored on a Lafayette device. A software program for data from a Hoggan device is not available on the website due to the additional cost of purchasing the data recording software for this device and issues experienced during testing with saving recorded data (See S1–S5 Files).

The inter-rater reliability was good to excellent for both peak force and RFD using both HHD devices. Nonetheless, agreement between assessors ranged from moderate to excellent for peak force and RFD, suggesting that although results between assessors are comparable, the results are not interchangeable. Previous research has found mixed inter-rater reliability in a range of populations for the assessment of muscle strength [34, 41–45]. Both assessors in the current study were male, with differing levels of experience. Prior research has compared reliability results for peak force analysis using a Hoggan micro*FET*2 HHD and found similar reliability between male and female assessors with varying levels of experience, height, and weight [46]. Previous studies have commented on the influence that assessor strength may have on HHD testing [34, 47]. In our experience, sufficient strength levels are required to control the movement of the patient, after which the technique of the assessor is likely to be just as important for obtaining valid results. During testing assessors should have a wide base of support, use their own body mass to lean into the participant and keep arms tucked in towards their body.

Closer examination of the results from each lower limb muscle group revealed that the hip musculature showed the strongest reliability and validity for measures of peak force and RFD. Previous research examining peak force has also found similar results for the assessment of hip strength using HHD in a range of populations [36, 37, 48–50]. Assessment of the ankle muscles demonstrated good to excellent reliability however validity was lower than expected. Previous research in a healthy population has also shown poor validity of HHD measures of plantarflexor strength in comparison with the KinCom [51]. Assessment of the ankle muscle groups is important, because the ankle plantarflexors have a primary role in power generation during walking [52] and the dorsiflexors are the lower body muscles most strongly associated with gait speed in people living with stroke [53]. Our mixed validity results in the current study and previous research [51] may have been caused by the ankle plantar/dorsiflexor attachment used on the KinCom. Participants reported difficulty in using the attachment, especially for ankle dorsiflexion, due to the lack of stabilisation that the attachment provides. Moreover, the ankle attachment does not fit tightly within the load cell, which may have resulted in measurement error. Similar comments have been made previously using the ankle inversion/eversion attachment on the KinCom [54]. Assessment of peak force of the knee extensors and flexors demonstrated good to excellent reliability and validity however validity of RFD measures for the knee extensors using both HHDs ranged from moderate to good. This may have been due to the higher levels of force and power generated in the knee extensors, leading to the assessors having difficulty in stabilising the HHD during the initial rapid rise in force, consequently impacting on measures of RFD. Therefore, if the knee extensors are the primary muscle of interest it may be necessary to consider external bracing during power assessment. Analysis of the SEM for intra-rater reliability for each device showed small percentages of the mean indicating low measurement error, with RFD higher than peak force values (<10% for peak force except one

measure and <20% for RFD except for one measure). The MDC results were also higher for RFD measures compared with peak force (<50% of the mean for RFD except two measures and <25% for peak force except for two measures). Analysis of the MDC for HHD measures of muscle strength and power may prove more informative in clinical populations than the healthy participants used in the current study.

The measurement of RFD has been widely used previously with a lack of consensus of which method is appropriate. After a comparison of various techniques for assessing RFD that were applicable to a HHD, this study utilised a peak 200ms iterative windowed time period method to determine peak RFD. Previous work has commented on the arbitrary nature of determining onset of contraction for calculation of RFD [55]. As such, this study did not determine the onset of contraction; rather RFD was identified using algorithms calculated from the first sample recorded to determine the peak RFD across the trial. This method ignores any erroneous recordings made by placing the HHD on the lower limb and as such the calculation of RFD will not include these initial recordings. Whilst increasing the duration of the window in the calculation of RFD may produce higher reliability results, a longer time window may include unwanted plateaus. We found the 200ms successive time window analysis technique to be robust to different sources of error during testing, however further research is needed in clinical populations to verify the findings of the current study.

Comparison of the Hoggan and Lafayette HHDs used in this study revealed no apparent differences between the devices in their reliability or validity for either measure of peak force or RFD. The inter-device reliability indicated that peak force results are interchangeable between the two different HHDs. Caution is necessary if interchanging RFD results between devices, as this study demonstrated mixed agreement between HHDs for measures of RFD. Additionally, both HHDs demonstrated mixed agreement with the KinCom for measures of peak force and RFD. The lack of agreement between devices for measures of RFD may be due to the different sampling rates employed by each device. Based on the results of the current study, there can be no recommendation as to which HHD should be used, with both devices demonstrating similar reliability and validity. One consideration for the future development of HHDs is the real-time calculation of RFD. Calculation of RFD on both of the devices chosen for this study currently requires post-testing analysis. The Hoggan device needs to be wirelessly connected to a computer during testing; with the software interface occasionally losing recorded data during collection (see S1–S5 Files). The Lafayette device stores raw data within the device, which can be downloaded to a laptop for analysis. After further testing, manufacturers should consider including RFD as an automated output on their device.

Study Limitations

The sample used in this study was a group of young, healthy, and physically active individuals. Even with the assessors bracing against a wall, the assessment of the knee extensors and ankle plantarflexors could not be completed for one male participant. Additionally, as can be seen in Tables 2 and 3, these two muscle groups recorded much higher strength and power values on the fixed dynamometer across all participants. It is likely that the assessment of muscle strength and power would be easier in those with muscle weakness, such as the elderly or those with neurological impairments. The findings of this study may therefore not be directly generalisable to some clinical populations. A recent review demonstrated that the reliability of HHDs is generally lower in healthy populations compared to clinical populations [34]. This could be due to the difficulties when testing stronger participants or lower inter-subject variability in healthy populations, compared to clinical. Nonetheless, the inclusion of healthy individuals does not discount the importance of our study, as normative data is required, albeit not

normalised to body mass, to allow comparison with healthy populations and therefore establishing reliability and validity in this group was considered essential.

Conclusions

Hand-held dynamometry is a reliable and valid tool for the assessment of isometric lower limb muscle strength and power, which may be valuable information particularly in clinical populations with gait impairments. Assessment of muscle strength and power in clinical populations using HHDs is warranted to determine the psychometric properties of these devices.

Competing Interests

The authors have declared that no competing interests exist.

Supporting Information

S1 File. Bland-Altman Plots indicating the validity of the Lafayette HHD in comparison with the KinCom for analysis of peak force (kg).
(PDF)

S2 File. Bland-Altman Plots indicating the validity of the Lafayette HHD in comparison with the KinCom for analysis of rate of force development (kg/s).
(PDF)

S3 File. Bland-Altman Plots indicating the validity of the Hoggan HHD in comparison with the KinCom for analysis of peak force (kg).
(PDF)

S4 File. Bland-Altman Plots indicating the validity of the Hoggan HHD in comparison with the KinCom for analysis of rate of force development (kg/s).
(PDF)

S5 File. Study outcome measures.
(XLSX)

Author Contributions

Conceived and designed the experiments: BFM KJB BA YHP GPW RAC. Performed the experiments: BFM LGP RM. Analyzed the data: BFM KJB YHP RM RAC. Contributed reagents/materials/analysis tools: BFM RAC. Wrote the paper: BFM LGP KJB BA YHP GPW RM RAC. Designed the software used in analysis: BFM RAC.

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Appendix H – Ethical approval and participant information consent forms

Study Two

-----Original Message-----
From: Kylie Pashley [mailto:Kylie.Pashley@acu.edu.au] On Behalf Of Res Ethics
Sent: Tuesday, 6 May 2014 9:25 AM
To: Ross Clark <Ross.Clark@acu.edu.au>; Benjamin Mentiplay <bfment001@myacu.edu.au>
Cc: Res Ethics <Res.Ethics@acu.edu.au>
Subject: 2014 93V Ethics application approved!

Dear Applicant,

Principal Investigator: Dr Ross Clark
Student Researcher: Mr Benjamin Mentiplay (HDR student) Ethics Register Number: 2014 93V
Project Title: Reliability and validity of low cost data acquisition systems Risk Level: Low Risk 3 Date Approved: 06/05/2014 Ethics Clearance End Date: 31/12/2014

This email is to advise that your application has been reviewed by the Australian Catholic University's Human Research Ethics Committee and confirmed as meeting the requirements of the National Statement on Ethical Conduct in Human Research.

This project has been awarded ethical clearance until 31/12/2014. In order to comply with the National Statement on Ethical Conduct in Human Research, progress reports are to be submitted on an annual basis. If an extension of time is required researchers must submit a progress report.

Whilst the data collection of your project has received ethical clearance, the decision and authority to commence may be dependent on factors beyond the remit of the ethics review process. The Chief Investigator is responsible for ensuring that appropriate permission letters are obtained, if relevant, and a copy forwarded to ACU HREC before any data collection can occur at the specified organisation. Failure to provide permission letters to ACU HREC before data collection commences is in breach of the National Statement on Ethical Conduct in Human Research and the Australian Code for the Responsible Conduct of Research. Further, this approval is only valid as long as approved procedures are followed.

If you require a formal approval certificate, please respond via reply email and one will be issued.

Decisions related to low risk ethical review are subject to ratification at the next available Committee meeting. You will be contacted should the Committee raises any additional questions or concerns.

Researchers who fail to submit a progress report may have their ethical clearance revoked and/or the ethical clearances of other projects suspended. When your project has been completed please complete and submit a progress/final report form and advise us by email at your earliest convenience. The information researchers provide on the security of records, compliance with approval consent procedures and documentation and responses to special conditions is reported to the NHMRC on an annual basis. In accordance with NHMRC the ACU HREC may undertake annual audits of any projects considered to be of more than low risk.

It is the Principal Investigators / Supervisors responsibility to ensure that:
1. All serious and unexpected adverse events should be reported to the HREC with 72 hours.
2. Any changes to the protocol must be approved by the HREC by submitting a Modification Form prior to the research commencing or continuing.
3. All research participants are to be provided with a Participant Information Letter and consent form, unless otherwise agreed by the Committee.

For progress and/or final reports, please complete and submit a Progress / Final Report form:
http://www.acu.edu.au/research/support_for_researchers/human_ethics/forms

For modifications to your project, please complete and submit a Modification form:
http://www.acu.edu.au/research/support_for_researchers/human_ethics/forms

Researchers must immediately report to HREC any matter that might affect the ethical acceptability of the protocol eg: changes to protocols or unforeseen circumstances or adverse effects on participants.

Please do not hesitate to contact the office if you have any queries.

Kind regards,
Kylie Pashley
on behalf of ACU HREC Chair, Dr Nadia Crittenden

Ethics Officer | Research Services
Office of the Deputy Vice Chancellor (Research) Australian Catholic University

THIS IS AN AUTOMATICALLY GENERATED RESEARCHMASTER EMAIL

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PARTICIPANT INFORMATION LETTER

PROJECT TITLE: Reliability and validity of low cost data acquisition systems
PRINCIPAL INVESTIGATOR: Dr Ross Clark
CO-INVESTIGATOR: Dr Brooke Adair
CO-INVESTIGATOR: Dr Gavin Williams
STUDENT RESEARCHER: Mr Benjamin Mentiplay
STUDENT'S DEGREE: Doctor of Philosophy (PhD)

Dear Participant,

You are invited to participate in the research project described below.

What is the project about?
The research project investigates the reliability and validity of low cost data acquisition systems in comparison to expensive laboratory devices. As these devices are inexpensive and portable, they could allow for quick and easy patient or athlete assessment without the need for expensive and time consuming laboratory analysis. Specifically, two gaming devices will be used (Nintendo Wii Balance Board and the Microsoft Kinect) to measure balance and kinematic data (e.g. joint angles) and a clinically feasible strength device will be used to measure muscle strength. These devices will be compared to their laboratory-based counterparts. These measures can provide valuable information on patient/athlete physical function including identifying physical dysfunction and monitoring change during recovery, which can lead to the development of individualised and targeted training programs. Initial pilot testing has shown promising results and if these devices are found to produce accurate and reliable data, it is hoped the devices could be implemented in to clinical practice to provide widespread and everyday use for assessment of patient/athlete function.

Who is undertaking the project?
This project is being conducted by Mr Benjamin Mentiplay and will form part of his Doctor of Philosophy (PhD) degree at Australian Catholic University under the supervision of Dr Ross Clark, Dr Brooke Adair and Dr Gavin Williams.

Are there any risks associated with participating in this project?
As the tasks involved in this research include physical activity (maximal muscle contractions, walking, low intensity running, hopping, stair descent and balance tests), there is a very low risk that you may experience physical discomfort. To minimise the risk, if you chose to participate, you will be required to complete a series of screening questions to ensure the tasks involved will not pose any risk to you. Additionally, adequate warm up and rest breaks between trials will be provided to minimise fatigue and water will be available to you to provide hydration. In the unlikely event of physical distress, a qualified First Aider will be present during all sessions to administer first aid. You will be referred to a medical practitioner should the injury be deemed sufficient to do so. In the unlikely event of psychological distress, you will be referred to ACU counselling services via the ACU website.

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What will I be asked to do?

You will be asked to attend two identical testing sessions one to eight days apart (each session will be approximately two and half hours), located at the biomechanics laboratory on the Lower Ground of the Daniel Mannix Building at ACU. The testing sessions will initially involve you filling out a medical history form and following this, basic anthropometric data will be recorded (e.g. height and mass) and then you will be prepared for testing. This will include placing reflective markers over your body (to measure kinematics).

Following preparation you will initially perform a series of balance tests, hopping tests, stair descent tests and then a series of walking (at two different speeds) and running trials across the laboratory floor. These trials will be used to measure balance as well as kinematics during gait. Finally, you will be required to perform maximal muscle contractions of eight lower limb muscle groups using your right lower limb, which involves you pushing or pulling as hard as you can against three different dynamometers. An appropriate warm up, water and rest breaks between trials will be provided to minimise fatigue.

How much time will the project take?

The project will involve two identical testing sessions, performed one to eight days apart at the same time and day. Each session will last approximately two and a half hours each.

What are the benefits of the research project?

At the conclusion of the study you are able, upon request, to gain access to your results of your strength levels and balance. Additionally, this study will demonstrate the reliability and validity of low cost data acquisition systems, which could be implemented into clinical practice in a variety of populations (e.g. athletes or chronic disease) which could allow for widespread and instantaneous results on measures of muscle strength, kinematics and balance.

Can I withdraw from the study?

Participation in this study is completely voluntary. You are not under any obligation to participate. If you agree to participate, you can withdraw from the study at any time without adverse consequences. Your participation or non-participation will have no bearing on your treatment within any academic unit at ACU. If you choose to withdraw, no additional data will be collected from you. Any data already collected will be retained by the researchers unless you do not wish for them to do so.

Will anyone else know the results of the project?

Aggregated results will be published in relevant peer-reviewed scientific journals once the study is complete. To ensure confidentiality of your data, individual results will not be published and will only be available to yourself and the researchers. Additionally, your data will be assigned a numerical code that only the researchers will be aware of. Therefore, your results will not be able to be identified by anyone apart from the researchers. The Microsoft Kinect includes a video camera that will be used to record data, however this data will be coded and stored on a password protected computer owned by the researchers, and as such you will not be able to be identified from any of the measurements taken during the study.

Will I be able to find out the results of the project?

It is intended that the results from this study be published (in aggregated form) in a peer-reviewed academic journal. Additionally, upon request, at the conclusion of the study you will be provided with

AUSTRALIAN CATHOLIC UNIVERSITY ACU exercise science

your individual results in comparison to the average of the group via email. Your individual results will not be accessible to anyone but the researchers and yourself.

Who do I contact if I have questions about the project?
If you have any questions about the project, you are free to contact Mr Benjamin Mentiplay via email (bfment001@myacu.edu.au).

What if I have a complaint or any concerns?
The study has been reviewed by the Human Research Ethics Committee at Australian Catholic University (Ethics Approval: 2014 93V). If you have any complaints or concerns about the conduct of the project, you may write to the Manager of the Human Research Ethics Committee care of the Office of the Deputy Vice Chancellor (Research).

Manager, Ethics
c/o Office of the Deputy Vice Chancellor (Research)
Australian Catholic University
North Sydney Campus
PO Box 968
NORTH SYDNEY, NSW 2059
Ph.: 02 9739 2519
Fax: 02 9739 2870
Email: res.ethics@acu.edu.au

Any complaint or concern will be treated in confidence and fully investigated. You will be informed of the outcome.

I want to participate! How do I sign up?
If you are willing to participate, or have any further questions please contact Mr Benjamin Mentiplay via email (bfment001@myacu.edu.au) to organise a time and day that suits you for testing.

Yours sincerely,

Dr Ross Clark	Dr Brooke Adair	Dr Gavin Williams	Mr Benjamin Mentiplay
Principal Investigator	Co-Investigator	Co-Investigator	Student Researcher
ACU	ACU	Epworth Hospital	ACU
Ross.Clark@acu.edu.au	Brooke.Adair@acu.edu.au	Gavin.Williams@epworth.org.au	bfment001@myacu.edu.au

AUSTRALIAN CATHOLIC UNIVERSITY ACU exercise science

CONSENT FORM
Copy for Participant to Keep

TITLE OF PROJECT: Reliability and validity of low cost data acquisition systems

PRINCIPAL INVESTIGATOR: Dr Ross Clark

CO-INVESTIGATOR: Dr Brooke Adair

CO-INVESTIGATOR: Dr Gavin Williams

STUDENT RESEARCHER: Mr Benjamin Mentiplay

I ..... *(the participant)* have read (*or, where appropriate, have had read to me)* and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction. I agree to participate in this study examining measures of muscle strength, kinematics, balance, hopping, stair descent and neuromuscular performance during maximal muscle contractions, walking, running and tests of balance, which will require attendance to two identical testing sessions lasting approximately two and a half hours each. I realise that I can withdraw my consent at any time without adverse consequences. If you choose to withdraw, no additional data will be collected from you. Any data already collected will be retained by the researchers unless you do not wish for them to do so. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify me in any way.

NAME OF PARTICIPANT: .....

SIGNATURE .....DATE:.....

SIGNATURE OF PRINCIPAL INVESTIGATOR:.....DATE:.....

SIGNATURE OF STUDENT RESEARCHER:.....DATE:.....

AUSTRALIAN CATHOLIC UNIVERSITY ACU exercise science

CONSENT FORM
Copy for Researcher to Keep

TITLE OF PROJECT: Reliability and validity of low cost data acquisition systems

PRINCIPAL INVESTIGATOR: Dr Ross Clark

CO-INVESTIGATOR: Dr Brooke Adair

CO-INVESTIGATOR: Dr Gavin Williams

STUDENT RESEARCHER: Mr Benjamin Mentiplay

I ..... *(the participant)* have read (*or, where appropriate, have had read to me)* and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction. I agree to participate in this study examining measures of muscle strength, kinematics, balance, hopping, stair descent and neuromuscular performance during maximal muscle contractions, walking, running and tests of balance, which will require attendance to two identical testing sessions lasting approximately two and a half hours each. I realise that I can withdraw my consent at any time without adverse consequences. If you choose to withdraw, no additional data will be collected from you. Any data already collected will be retained by the researchers unless you do not wish for them to do so. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify me in any way.

NAME OF PARTICIPANT: .....

SIGNATURE .....DATE:.....

SIGNATURE OF PRINCIPAL INVESTIGATOR: .....DATE:.....

SIGNATURE OF STUDENT RESEARCHER: .....DATE:.....

Study Three and Four – Australian site

-----Original Message-----
From: Kylie Pashley [mailto:Kylie.Pashley@acu.edu.au] On Behalf Of Res Ethics
Sent: Friday, 17 October 2014 9:10 AM
To: Ross Clark <Ross.Clark@acu.edu.au>; Benjamin Mentiplay <bfment001@myacu.edu.au>
Cc: Res Ethics <Res.Ethics@acu.edu.au>
Subject: 2014 281V Registration of External Ethics Approval

Dear Ross,

Principal Investigator: Dr Ross Clark
Student Researcher: Mr Benjamin Mentiplay (HDR student) Ethics Register Number: 2014 281V
Project Title: Associations between physical function and isometric lower limb strength following stroke Risk Level: Multi Site Date Approved: 17/10/2014 Ethics Clearance End Date: 01/06/2016

The Australian Catholic University Human Research Ethics Committee has considered your application for registration of an externally approved ethics protocol and notes that this application has received ethics approval from Epworth HealthCare [Reference: 637-14].

The ACU HREC accepts the ethics approval with no additional requirements, save that ACU HREC is informed of any modifications of the research proposal and that copies of all progress reports and any other documents be forwarded to it. Any complaints involving ACU staff must also be notified to ACU HREC (National Statement 5.3.3)

We wish you well in this research project.

Regards,

Kylie Pashley
on behalf of ACU HREC Chair, Dr Nadia Crittenden Ethics Officer | Research Services Office of the Deputy Vice Chancellor (Research) res.ethics@acu.edu.au

Epworth HealthCare
Excellence, Everywhere, Every Day

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F +613 9427 0353

www.epworth.org.au
ABN 97 420 694 950

02 June 2014

A/Prof Gavin Williams
Specialist Neurological Physiotherapist and Research Fellow
Epworth Hospital
89 Bridge Rd
Richmond 3121

Dear Gavin

Re: Epworth Study No: 637-14
Title: Associations between physical function and isometric lower limb strength following stroke.

The Epworth HealthCare Board of Management approved your study at the meeting held on Wednesday 28 May 2014.

Please note that the study has been given the reference number 637-14. Any correspondence relating to the project should quote this reference.

The following documents were reviewed and approved by the HREC at the meeting held on 07 May 2014:

- NEAF signed 16 April 2014
- VSM signed 16 April 2014
- Protocol (no version number/date)

Thank you for submitting your amendments, the following documents are approved and meet with the recommendations of the HREC Committee:

- Letter dated 26 May 2014 explaining participant numbers and investigator affiliation
- PICF version 2 dated 26 May 2014

To ensure compliance with NHMRC Guidelines, Guidelines for Good Clinical Research Practice (GCRP) in Australia, and in line with Epworth HealthCare's HREC policy, it is the Principal Investigator's responsibility and a condition of HREC approval, to ensure that:

- The HREC is notified of anything that might warrant review of the ethical approval of the project, including unforseen events that might affect the ethical acceptability of the project.
- The HREC is notified of all Serious Adverse Events (SAEs) or Serious Unexpected Adverse Reactions (SUSARs).
- Proposed amendments to the research protocol or conduct of the research that may affect the ethical acceptability of the project are submitted to the HREC (including any relevant attachments).
- Proposed changes to the personnel involved in the study are submitted to the HREC.
- The HREC must be provided with an annual progress report for the study on the anniversary of approval.
- The HREC must also be provided with a final report upon completion of the study.
- The HREC must be notified, giving reasons if the study is discontinued at the site before the expected date of completion.

I enclose your Certificate of Approval, which notes the terms and conditions of this approval. You are requested to acknowledge these terms and conditions by **signing the duplicate copy and returning it to me as soon as possible.**

If any presentations or publications arise from this study, please ensure that Epworth HealthCare receives appropriate recognition and copies of presentations and publications are provided to HREC Coordinator for Committee review and file inclusion.

The Epworth HealthCare Human Research Ethics Committee is established under the National Health and Medical Research Council guidelines and adheres to the Guidelines of Good Clinical Practice, and HREC membership comprises of the following:

Chair – Reverend Professor	Epworth Executive member
Minister of Religion	Lawyer
Board of Management Member	Medical Practitioners
Psychological Researcher	Lay Persons
Research, Data Collection and Analysis experts	

There is no set term of Office for Members of this Committee.

Please feel free to contact me if you have any queries or require assistance.

Kind regards,

Hilary Young
HREC Coordinator
Mail Box 4
89 Bridge Road
Richmond Vic 3121

Epworth HealthCare

Human Research Ethics Committee Certificate of Approval

Project Title:	**Associations between physical function and isometric lower limb strength following stroke.**
Principal Investigator:	**A/Prof Gavin Williams**
Epworth study no:	**637-14**
HREC Meeting date:	**07 May 2014**
Board of Management approval:	**28 May 2014**
Duration of Project:	**01 June 2014 to 01 June 2016**

Alan R. Kinkade
Group Chief Executive

Terms and conditions of approval:
The Principal Investigator is required to notify the Human Research Ethics Committee of the following;
All Projects:

1. Must comply with the Australian code for Responsible Conduct of Research (2007) – http://www.nhmrc.gov.au/publications/synopses/files/r39.pdf
2. Any proposed changes to the protocol or approved documentation or the addition of documents (including flyers, brochures, advertising materials etc) must be submitted to the Human Research Ethics Committee for approval prior to implementation
3. The Principal Investigator must notify HREC of
   a. Any serious adverse effects of the study on participants and steps taken to deal with them
   b. Any unforeseen events (e.g. protocol violations or complaints)
   c. Investigators withdrawing from or joining the project
4. A Progress Report must be submitted annually and at the conclusion of the project
5. Epworth HealthCare HREC approval must remain current for the entire duration of the project. If the project is not completed in the allocated time a renewal request must be submitted to the HREC. Investigators undertaking projects without current HREC approval risk their indemnity, funding and publication rights

Clinical Trials:

6. Must comply with Good Clinical Practice (GCP) http://www.tga.gov.au/docs/pdf/euguide/ich/ich13595.pdf
7. Must report all internal (occurring at Epworth HealthCare) Serious Adverse Events (SAE) to the sponsor and the HREC within 72 hours of occurrence
8. Must report all Suspected Unexpected Serious Adverse Reactions (SUSARS) to the Therapeutic Goods Administration (TGA). For sponsored studies, the sponsor may take this responsibility

I, ..., accept the terms and conditions set out above.

Signature of Researcher: ..... Date: .....

Participant Information Sheet/Consent Form

Non-Interventional Study - *Adult providing own consent*

Title	Associations between physical function and isometric lower limb strength following stroke
Protocol Number	637-14
Principal Investigators	Dr Gavin Williams (Epworth Healthcare) Ms Kelly Bower (Australian Catholic University, Royal Melbourne Hospital) Mr Benjamin Mentiplay (ACU) Dr Ross Clark (ACU) Dr Brooke Adair (ACU)
Location	Epworth Healthcare

Part 1 What does my participation involve?

1 Introduction

You are invited to take part in this research project, titled 'associations between strength and walking following stroke'. This is because you are receiving rehabilitation at Epworth Healthcare following a stroke. The research project is aiming to examine the relationships between lower limb muscle strength and walking performance following stroke.

This Participant Information Sheet/Consent Form tells you about the research project. It explains the tests and research involved. Knowing what is involved will help you decide if you want to take part in the research. Please read this information carefully. Ask questions about anything that you don't understand or want to know more about. Before deciding whether or not to take part, you might want to talk about it with a relative, friend or local doctor.

Participation in this research is voluntary. If you do not wish to take part, you do not have to. Your decision whether to take part or not to take part, or to take part and then withdraw, will not affect your routine treatment, your relationship with those treating you, the research team or your relationship with anyone within Epworth Healthcare.

If you decide you want to take part in the research project, you will be asked to sign the consent section. By signing it you are telling us that you:
- Understand what you have read
- Consent to take part in the research project
- Consent to the tests and research that are described
- Consent to the use of your personal and health information as described.

You will be given a copy of this Participant Information and Consent Form to keep.

2 What is the purpose of this research?

Many factors impact upon walking following stroke, such as strength, balance and coordination. The aim of this project is to determine how much muscle strength contributes to walking ability following stroke. Strength will be measured using a strength testing device (hand-held dynamometer) and walking will be measured using a variety of clinical and laboratory-based assessments, including walking and balance tests.

This project will provide clinicians and researchers with a perspective on the relationships between lower limb strength and walking following stroke. The project aims to provide a better understanding of this relationship, so that physiotherapists know how much and what type of strength training they should be implementing during treatment following stroke.

The results of this research will be used by Mr Benjamin Mentiplay to obtain a Doctor of Philosophy (PhD) degree. This research has been partly funded by and conducted in collaboration with Australian Catholic University.

3 What does participation in this research involve?

It is anticipated that 68 participants will be involved in this project. Participants will be required to attend two testing sessions approximately one week apart. Prior to any testing, participants will be asked to read and sign an informed consent form. Eligible participants will be identified by physiotherapists who screen anybody who would be suitable for participation in this project.

The initial testing session will be conducted at your hospital where you are receiving physiotherapy and will last approximately 60 minutes. The following tests will be performed, without the use of any assistive devices such as canes or walkers:

- A cognitive screening test (Abbreviated Mental Test Score)
- Walking test (10m walk test)
- Balance test on a Nintendo Wii Balance Board
- Strength testing of your lower limb muscles

The second testing session will either take place at your hospital or at Australian Catholic University (ACU). It is our preference, if you are able to, to attend your second session at ACU. This second session at ACU will last between 60 and 90 minutes. You will be asked to:

- Have reflective markers attached to your skin
- Perform a series of walking tests across the laboratory
- Perform strength testing of your lower limb muscles

If your second testing session is at your hospital, you will repeat the same procedures as your first testing session. The second session will be your last testing session and you will no longer be required to participate in this project. This research project has been designed to make sure the researchers interpret the results in a fair and appropriate way and avoids researchers or participants jumping to conclusions.

There are no costs associated with participating in this research project, nor will you be paid. You will be reimbursed for travel expenses if you attend your second testing session at Australian Catholic University in Fitzroy. You will be reimbursed via a $50 Coles Group & Myer gift card. If you decide to participate in this research project, the researchers will inform your physiotherapist. Additionally, we will also access your medical history from your hospital so that we can describe the group of participants that we recruit.

4 What do I have to do?

All you are required to do to participate in this project is to attend two testing sessions (described above) lasting approximately 60-90 minutes each, one to eight days apart. There are no restrictions placed on your activities, diet or medication whilst participating in this project.

5 Other relevant information about the research project

This project is being conducted in collaboration with clinicians at Epworth Healthcare and Royal Melbourne Hospital and researchers at Australian Catholic University. The data recorded during this project will be used to contribute towards Mr Mentiplay attaining a Doctor of Philosophy degree at Australian Catholic University.

6 Do I have to take part in this research project?

Participation in any research project is voluntary. If you do not wish to take part, you do not have to. If you decide to take part and later change your mind, you are free to withdraw from the project at any stage without adverse consequences.

Your decision whether to take part or not to take part, or to take part and then withdraw, will not affect your routine treatment, your relationship with those treating you or your relationship with anyone within Epworth Healthcare.

If you do decide to take part, you will be given this Participant Information and Consent Form to sign and you will be given a copy to keep.

7 What are the alternatives to participation?

You do not have to take part in this research project to receive treatment at this hospital. The assessments to be conducted during this project involve standard clinical tests to be performed in additional to your standard therapy and as such no treatment will be withheld if you decide not to participate.

8 What are the possible benefits of taking part?

We cannot guarantee or promise that you will receive any benefits from this research. Participants will have their physical function assessed using a variety of outcome measures. These results may be passed on to your physiotherapist who could use this information for the development of targeted rehabilitation programs.

Your participation in this project will aid researchers and clinicians to gain a better understanding of the relationships between strength and physical function. This information could be used to understand how problems, such as muscle weakness, relate to the ability to walk. This could help physiotherapists to develop more effective (or better) treatment programs following stroke.

9 What are the possible risks and disadvantages of taking part?

There are minimal risks involved in participating in this project. This project involves physical testing of your balance, strength and walking ability that involves exercise. However, these tests are routine clinical assessments. You will be monitored throughout testing for any signs of fatigue or discomfort. There will also be adequate rest breaks and water provided during testing. If you feel any discomfort during the testing procedures you should alert the researchers immediately. You will be monitored thereafter to determine if you are able or unable to continue with the testing session. There will always be one researcher close by to provide physical support should you require. The researchers involved during testing have current first aid qualifications and physiotherapists will be present in the unlikely case of any adverse event. There may be additional risks that the researchers do not expect or are unaware of. You should tell the researchers immediately about any new or unusual symptoms.

10 Can I have other treatments during this research project?

Yes, you are free to continue with your usual treatment and/or medication as advised by your physiotherapist and medical team.

11 What if I withdraw from this research project?

You are free to withdraw from this project at any time without it affecting your treatment or relationships with the researchers or anyone within Epworth Healthcare. If you decide to withdraw from this research project, please notify a member of the research team before you withdraw.

If you do withdraw your consent during the research project, the researchers will not collect additional information from you, although information already collected will be retained to ensure that the results of the research project can be measured properly and to comply with law. If you do not want them to do this, please inform the researchers.

12 What happens when the research project ends?

You have no obligations after your testing sessions are completed. The results from this project will be used in both Mr Mentiplay's thesis but also will be published in relevant medical journals. If you would like a copy of your results you are welcome to contact the research team to receive your individual results after testing and a summary of the research project.

Part 2 How is the research project being conducted?

13 What will happen to information about me?

By signing the consent form you consent to the study research staff collecting and using personal information about you for the research project. Any information obtained in connection with this research project that can identify you will remain confidential. All data collected during this project will be coded to avoid identification, and as such, no names will be present on any data recorded. All data will be stored in either a locked filing cabinet or on a password protected computer. Only the researchers listed on this document will have access to your data. Your information will only be used for the purpose of this research project and it will only be disclosed with your permission, except as required by law. All data will be destroyed after five years of completion of the project.

Information about you may be obtained from your health records held at this and other health services for the purpose of this research. By signing the consent form you agree to the research team accessing health records relevant to your participation in this research project.

It is anticipated that the results of this research project will be published and/or presented in a variety of forums. In any publication and/or presentation, information will be provided in such a way that you cannot be identified, except with your permission. Only aggregated data will be used in any publications and/or presentations and as such your data will not be identifiable. Information about your participation in this research project may be recorded in your health records to be used by your physiotherapist for your rehabilitation.

In accordance with relevant Australian and/or Victorian privacy and other relevant laws, you have the right to request access to the information collected and stored by the research team about you. You also have the right to request that any information with which you disagree be corrected. You are able to request your personal results as well as a summary of the project results from the research team. If you would like this information, please contact one of the research team members listed at the end of this letter.

14 Complaints and compensation

If you suffer any injuries or complications as a result of this research project, you should contact the research team as soon as possible and you will be assisted with arranging appropriate

medical treatment. If you are eligible for Medicare, you can receive any medical treatment required to treat the injury or complication, free of charge, as a public patient in any Australian public hospital.

15 Who is organising and funding the research?

This research project is being conducted by Dr Gavin Williams, Ms Kelly Bower, Mr Benjamin Mentiplay, Dr Ross Clark and Dr Brooke Adair. This project is partly funded by Australian Catholic University. No member of the research team will receive a personal financial benefit from your involvement in this research project.

16 Who has reviewed the research project?

All research in Australia involving humans is reviewed by an independent group of people called a Human Research Ethics Committee (HREC). The ethical aspects of this research project have been approved by the HREC of Epworth Healthcare. This project will be carried out according to the *National Statement on Ethical Conduct in Human Research (2007)*. This statement has been developed to protect the interests of people who agree to participate in human research studies.

17 Further information and who to contact

The person you may need to contact will depend on the nature of your query. If you want any further information concerning this project or if you have any medical problems which may be related to your involvement in the project (for example, any side effects), you can contact Mr Benjamin Mentiplay on 0400 801 627 (bfment001@myacu.edu.au) or any of the following people:

Clinical contact person

Name	Dr Gavin Williams
Position	Specialist Neurological Physiotherapist and Research Fellow
Telephone	(03) 9426 8727
Email	Gavin.Williams@epworth.org.au

For matters relating to research at the site at which you are participating, the details of the local site complaints person are:

Complaints contact person

Name	Hilary Young
Position	HREC Coordinator/Executive Officer
Telephone	(03) 9426 8806
Email	Hilary.Young@epworth.org.au

If you have any complaints about any aspect of the project, the way it is being conducted or any questions about being a research participant in general, then you may contact:

Reviewing HREC approving this research and HREC Executive Officer details

Reviewing HREC name	Epworth HREC
HREC Executive Officer	Hilary Young
Telephone	(03) 9426 8806
Email	Hilary.Young@epworth.org.au

Consent Form - *Adult providing own consent*

Title	Associations between gait and isometric lower limb strength following stroke
Protocol Number	637-14
Principal Investigators	Dr Gavin Williams (Epworth Healthcare) Ms Kelly Bower (Australian Catholic University, Royal Melbourne Hospital) Mr Benjamin Mentiplay (ACU) Dr Ross Clark (ACU) Dr Brooke Adair (ACU)
Location	Epworth Healthcare

Declaration by Participant

I have read the Participant Information Sheet or someone has read it to me in a language that I understand.

I understand the purposes, procedures and risks of the research described in the project.

I have had an opportunity to ask questions and I am satisfied with the answers I have received.

I freely agree to participate in this research project as described and understand that I am free to withdraw at any time during the project without affecting my future health care.

I understand that I will be given a signed copy of this document to keep.

I give permission for my doctors, other health professionals, hospitals or laboratories outside this hospital to release information to the research team concerning my condition and treatment for the purposes of this project. I understand that such information will remain confidential.

I give permission for the research team to release my personal results from this project to my treating physiotherapist.

Name of Participant (please print) _____

Signature _____ Date _____

Name of Witness* to Participant's Signature (please print) _____

Signature _____ Date _____

* Witness is not to be the investigator, a member of the study team or their delegate. In the event that an interpreter is used, the interpreter may not act as a witness to the consent process. Witness must be 18 years or older.

Declaration by Senior Researcher†

I have given a verbal explanation of the research project, its procedures and risks and I believe that the participant has understood that explanation.

Senior Researcher† (please print) _____

Signature _____ Date _____

† A senior member of the research team must provide the explanation of, and information concerning, the research project.

Note: All parties signing the consent section must date their own signature.

Form for Withdrawal of Participation - *Adult providing own consent*

Title	Associations between physical function and isometric lower limb strength following stroke
Protocol Number	637-14
Principal Investigators	Dr Gavin Williams (Epworth Healthcare) Ms Kelly Bower (Australian Catholic University, Royal Melbourne Hospital) Mr Benjamin Mentiplay (ACU) Dr Ross Clark (ACU) Dr Brooke Adair (ACU)
Location	Epworth Healthcare

Declaration by Participant

I wish to withdraw from participation in the above research project and understand that such withdrawal will not affect my routine treatment, my relationship with those treating me or my relationship with Epworth Healthcare.

Name of Participant (please print) _____

Signature _____ Date _____

In the event that the participant's decision to withdraw is communicated verbally, the Researchers will need to provide a description of the circumstances below.

Declaration by Senior Researcher†

I have given a verbal explanation of the implications of withdrawal from the research project and I believe that the participant has understood that explanation.

Name of Study Doctor/
Senior Researcher† (please print) _____

Signature _____ Date _____

† A senior member of the research team must provide the explanation of and information concerning withdrawal from the research project.

Note: All parties signing the consent section must date their own signature.

Study Three and Four – Singaporean site

SingHealth
Defining Tomorrow's Medicine

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Fax: (65) 6557 2464
Singapore Health Services Pte Ltd
31 Third Hospital Avenue
#03-03 Bowyer Block C
Singapore 168753
www.singhealth.com.sg
UEN No 200002698Z

CIRB Ref: **2015/2562**

20 Aug 2015

Dr Tan May Leng Dawn
Department of Physiotherapy
Singapore General Hospital

Dear Dr Tan

SINGHEALTH CENTRALISED INSTITUTIONAL REVIEW BOARD (CIRB) APPROVAL

Protocol Title: Associations between physical function and isometric lower limb strength following stroke

We are pleased to inform you that the SingHealth CIRB F has approved the above research project to be conducted in Singapore General Hospital.

The documents reviewed are:

a) CIRB Application Form dated 7 Aug 2015
b) Protocol: Version 1.4 dated 22 Jun 2015
c) Participant Information Sheet and Consent Form: Version 1.5 dated 6 Aug 2015
d) Data Collection Sheet: Version 1.2 dated 5 Jun 2015
e) Data Collection Sheet (Session 2): Version 1.3 dated 11 Jun 2015
f) Modified Abbreviated Mental Test Score – Singaporean
g) Protocol for strength assessment using hand-held dynamometry

The SingHealth CIRB operates in accordance with the ICH/ Singapore Guideline for Good Clinical Practices, and with the applicable regulatory requirement(s).

The approval period is from **20 Aug 2015 to 20 Jul 2016.** The reference number for this study is CIRB Ref: 2015/2562. Please use this reference number for all future correspondence.

The following are to be observed upon SingHealth CIRB Approval:

1. No subject should be admitted to the trial before the Health Sciences Authority issues the Clinical Trial Certificate. (only applicable for drug-related studies).

2. The Principal Investigator should ensure that this study is conducted in compliance with the Singapore Guideline for Good Clinical Practice, the ethical guidelines of which are applicable to all studies to be carried out, and to ensure that the study is carried out in accordance to the guidelines and the submitted protocol. The Principal Investigator should meet with his collaborator(s) regularly to assess the progress of the study, and be familiar and comply with all applicable research policies in the Institution.

3. No deviation from, or changes of, the protocol should be initiated without prior written SingHealth CIRB approval of an appropriate amendment, except when necessary to

eliminate immediate hazards to the subjects or when the change(s) involve(s) only logistical or administrative aspects of the trial (e.g. change of monitor(s), telephone number(s).

4. Only the approved Participant Information Sheet and Consent Form should be used. It must be signed by each subject prior to enrolling in the study and initiation of any protocol procedures. Two copies of the Informed Consent Form should be signed and dated. Each subject or the subject's legally accepted representative should be given a copy of the signed consent form. The remaining copy should be kept by the PI / medical record.

5. The Principal Investigator should report promptly to the SingHealth CIRB of:
   i. Deviations from, or changes to the protocol including those made to eliminate immediate hazards to the trial subjects.
   ii. Changes increasing the risk to subjects and/or affecting significantly the conduct of the trial.
   iii. All serious adverse events (SAEs) and adverse drug reaction (ADRs) that are both serious and unexpected.
   iv. New information that may affect adversely the safety of the subjects or the conduct of the trial.
   v. Completion of the study.

6. Study Status Report should be submitted to the SingHealth CIRB for the following:
   i. Annual review: Status of the study should be reported to the SingHealth CIRB at least annually using the Study Status Report.
   ii. Study renewal: the Study Status Report is to be submitted at least two months prior to the expiry of the approval period. A valid SingHealth CIRB renewal is essential, as any research performed outside of an approved time frame is not legal, and thus not covered by the hospital's research insurance in case of unexpected adverse reactions.
   iii. Study completion or termination: the Final Report is to be submitted within three months of study completion or termination.

Yours sincerely,

Dr Aloysius Ho Yew Leng
Chairman
SingHealth Centralised Institutional Review Board F

Enc.

cc: Institution Representative, SGH
Head, Department of Physiotherapy, SGH

Annex 1

LIST OF CIRB F MEMBERS INVOLVED IN THE REVIEW ON 21 JUL 2015			
Name	**CIRB Membership**	**Designation, Institution**	**Gender**
Dr Aloysius Ho Yew Leng	Chairman	Senior Consultant Singapore General Hospital Department of Haematology	Male
A/Prof Cynthia Ruth Goh-Fung	Alternate Member	Senior Consultant National Cancer Centre Department of Palliative Medicine	Female
BG (Ret) Prof Lionel Lee Kim Hock	Member	Executive Vice Dean, Administration Nanyang Technological University Lee Kong Chian School of Medicine	Male
Dr Colin Phipps Diong	Member	Consultant Singapore General Hospital Department of Haematology	Male
A/Prof Edward Poon Wing Hong	Member	Director of Nursing Ang Mo Kio- Thye Hua Kwan Hospital	Male
Ms Cindy Ng Li Whye	Alternate Member	Principal Physiotherapist Singapore General Hospital Department of Physiotherapy	Female
Dr Iain Tan Bee Huat	Member	Associate Consultant, Division of Medical Oncology, National Cancer Centre	Male
Mr Tan Woon Tiang	Alternate Member	Retiree, Member of the Community	Male

SingHealth

PARTICIPANT INFORMATION SHEET

You are being invited to participate in a research study.

Before you take part in this research study, the study must be explained to you and you must be given the chance to ask questions. Please read carefully the information provided here. If you agree to participate, please sign the informed consent form. You will be given a copy of this document to take home with you.

STUDY INFORMATION

Protocol Title:

Associations between physical function and isometric lower limb strength following stroke

Principal Investigator:

Dr Dawn Tan, Principal Physiotherapist, Singapore General Hospital

Contact number: 8125 2985

Research support:

This research is supported by the Australian Catholic University.

PURPOSE OF THE RESEARCH STUDY

You are being invited to participate in a research study that is investigating how different muscle groups affect your physical function. Many factors impact upon walking following stroke, such as strength, balance and coordination. The aim of this project is to determine how much muscle strength contributes to walking ability following stroke. Strength will be measured using a strength testing device (hand-held dynamometer) and walking will be measured using a variety of clinical and laboratory based assessments, including walking and balance tests. This project will provide clinicians and researchers with a perspective on the relationships between lower limb strength and walking following stroke. The project aims to provide a better understanding of this relationship, so that physiotherapists know how much and what type of strength training they should be implementing during treatment following stroke.

You were selected as a possible participant in this study because you are undergoing outpatient rehabilitation after a stroke at Singapore General Hospital. This study aims to recruit 140 participants from Singapore General Hospital and Epworth Healthcare in Melbourne, Australia.

STUDY PROCEDURES AND VISIT SCHEDULE

If you agree to take part in this study, you will be asked to go through the same assessment process as all other participants. Two assessments will be performed approximately one week apart.

At the assessments, we will take measures of your height and weight, and ask you some questions about your previous medical conditions. The research team will require access to your personal medical record to obtain details about your medical condition. We will also do

a quick test of your memory and thinking. Following this, you will be assessed on walking and balance tasks, such as walking at a comfortable pace and balancing on the spot. We will also obtain measures of your lower limb strength through a series of tests of your legs. The testing session will take approximately 60 minutes to complete. The second test approximately one week later will involve more complex analysis of your physical function (e.g. walking) using three-dimensional motion analysis.

Schedule of visits and procedures:

Visit 1: One hour session at Singapore General Hospital, Department of Physiotherapy or Specialist Outpatient Clinic

Visit 2: One to two hour session, approximately one week after visit 1 at Academia

YOUR RESPONSIBILITIES IN THIS STUDY

If you agree to participate in this study, you should:

- Keep your study appointments. If it is necessary to miss an appointment, please contact the study staff to reschedule as soon as you know you will miss the appointment.
- Be prepared to visit the hospital *twice, approximately one week apart* and undergo all the procedures that are outlined above. To minimise inconvenience to you, the study assessment will be conducted on the same day as your hospital outpatient appointment where possible.

WITHDRAWAL FROM STUDY

You are free to withdraw your consent and discontinue your participation at any time without prejudice to you or effect on your medical care. If you decide to stop taking part in this study, please notify a member of the research team.

If you withdraw from the study, the study staff will not collect additional personal information from you, although personal information already collected will be retained to ensure that the results of the research project can be measured properly. You should be aware that data collected up to the time you withdraw will form part of the research project results. You will also have to return any study related materials you may have.

The Principal Investigator of this study may stop your participation in the study at any time for one or more of the following reasons:

- Failure to follow the instructions of the Principal Investigator and/or study staff.
- The Principal Investigator decides that continuing your participation could be harmful.
- The study is cancelled.

WHAT IS NOT STANDARD CARE OR EXPERIMENTAL IN THIS STUDY

Although the walking and balance assessments and questionnaires may be part of standard rehabilitation, in this study these assessments are being performed for the purposes of the research. Additionally, we will be using a Microsoft Kinect and three-dimensional motion analysis at the second session, which will track your movement during testing to examine different aspects of your function. This is a low cost device that has previously been used for research in Australia. The use of a three-dimensional motion analysis system is also not standard care, but has been used many times before for research.

POSSIBLE RISKS, DISCOMFORTS AND INCONVENIENCES

The assessment procedures are unlikely to have any side effects, however, as with any form of physical activity there are possible risks associated with participation. Possible risks include pain, fatigue or injury. Rest breaks will be provided throughout testing during the walking and strength tests to minimise these risks. The treatment does not involve any invasive procedures.

Your medical history will be thoroughly screened and the assessment sessions will be performed under the supervision of an experienced physiotherapist. You will be closely monitored for any adverse effects such as pain, fatigue or other symptoms.

There may be additional risks that the researchers do not expect or do not know about. You will need to tell a member of the research team immediately about any new or unusual symptoms.

POTENTIAL BENEFITS

There is no assurance you will benefit from this study.

Your participation will allow us to determine the usefulness of these types of assessments. It will also give us new information on which muscle groups aid in physical function after stroke. This research will help to improve our understanding on how to improve care to assist people with stroke in the future.

ALTERNATIVES

If you are interested in the study but have concerns over attending two sessions, you are able to attend only the first session. You can choose not to take part in the second session but still participate in the first session of the study. Please let the study team member know if you would like to opt out of the second session and indicate this in the consent section below.

If you choose not to take part in this study, the alternative is to have what is considered standard care for your condition. In our institution this would be the usual clinical walking and balance tests with the physiotherapist.

This standard care has the usual benefits of a routine physiotherapy assessment and poses the same possible risks as associated with physical activity which includes pain, fatigue or injury.

SUBJECT'S RIGHTS

Your participation in this study is entirely voluntary. Your questions will be answered clearly and to your satisfaction.

In the event of any new information becoming available that may be relevant to your willingness to continue in this study, you or your legal representative will be informed in a timely manner by the Principal Investigator or his/her representative.

By signing and participating in the study, you do not waive any of your legal rights to revoke your consent and withdraw from the study at any time.

CONFIDENTIALITY OF STUDY AND MEDICAL RECORDS

Information collected for this study will be kept confidential. Your records, to the extent of the applicable laws and regulations, will not be made publicly available. Only your Investigator(s) will have access to the confidential information being collected.

However, the Regulatory Agencies, Institutional Review Board and Ministry of Health will be granted direct access to your original medical records to check study procedures and data, without making any of your information public.

By signing the Informed Consent Form attached, you or your legal representative are authorizing (i) collection, access to, use and storage of your "Personal Data, and (ii) disclosure to authorised service providers and relevant third parties.

"Personal Data" means data about you which makes you identifiable (i) from such data or (ii) from that data and other information which an organisation has or likely to have access. This includes medical conditions, medications, investigations and treatment history.

Research arising in the future, based on this Personal Data, will be subject to review by the relevant institutional review board.

By participating in this research study, you are confirming that you have read, understood and consent to the SingHealth Data Protection Policy- the full version is available at www.singhealth.com.sg/pdpa. Hard copies are also available on request.

Data collected and entered into the *Data Collection Form(s)* are the property of Singapore General Hospital. In the event of any publication regarding this study, your identity will remain confidential.

COSTS OF PARTICIPATION

If you take part in this study, the following will be performed at no charge to you:

- Two 60-120 minute assessments of your balance, strength and movement

You will not be paid for your participation.

RESEARCH RELATED INJURY AND COMPENSATION

The Hospital does not make any provisions to compensate study subjects for research related injury. However, compensation may be considered on a case-by-case basis for unexpected injuries due to non-negligent causes.

By signing this consent form, you will not waive any of your legal rights or release the parties involved in this study from liability for negligence.

WHO TO CONTACT IF YOU HAVE QUESTIONS

If you have questions about this research study or in the case of any injuries during the course of this study, you may contact the Study Team Member:

Dr Dawn Tan

Principal Physiotherapist, Singapore General Hospital

Contact number: 8125 2985

This study has been reviewed by the SingHealth Centralised Institutional Review Board for ethics approval. If you have questions about your rights as a participant, you can call the SingHealth Centralised Institutional Review Board at 6323 7515 during office hours (8:30 am to 5:30pm). If you have any complaints about this research study, you may contact the Principal Investigator or the SingHealth Centralised Institutional Review Board.

CONSENT BY RESEARCH SUBJECT

Details of Research Study

Protocol Title:
Associations between physical function and isometric lower limb strength following stroke

Principal Investigator:
Dr Dawn Tan
Principal Physiotherapist
Singapore General Hospital
Contact number: 8125 2985

Subject's Particulars

Name: NRIC No.:
Address:
Sex: Female/Male Date of birth _____
dd/mm/yyyy
Race: Chinese/ Malay/ Indian /Others (please specify) _____

Do you want to participate in the second session? (please circle) YES NO

I, _____(NRIC/Passport No._____)
(Name of patient)
agree to participate in the research study as described and on the terms set out in the Patient Information Sheet.

I have fully discussed and understood the purpose and procedures of this study. I have been given the Participant Information Sheet and the opportunity to ask questions about this study and have received satisfactory answers and information.

I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reasons and without my medical care being affected.

By participating in this research study, I confirm that I have read, understood and consent to the SingHealth Data Protection Policy. I also consent to the use of my Personal Data for the purposes of engaging in related research arising in the future.

_____ _____
Signature/Thumbprint (Right / Left) of participant Date of signing

To be filled by parent / legal guardian / legal representative, where applicable

I, _____ hereby give consent for the above participant to participate in
(parent / legal guardian)
the proposed research study. The nature, risks and benefits of the study have been explained clearly to me and I fully understand them.

_____ _____
Signature/Thumbprint (Right / Left) of parent /legal guardian Date of signing

Translator Information (if required)

The study has been explained to the participant/ legal representative in

_____ by _____.
Language Name of translator

To be filled by witness, where applicable

An impartial witness should be present during the entire informed consent discussion if a subject or the subject's legal representative is unable to read. After the written informed consent form and any written information to be provided to subjects, is read and explained to the subject or the subject's legal representative, and after the subject or the subject's legal representative has orally consented to the subject's participation in the study and, if capable of doing so, has signed and personally dated the consent form, the witness should sign and personally date the consent form.

Witnessed by: _____ _____
Name of witness Designation of witness

_____ _____
Signature of witness Date of signing

Investigator's Statement

I, the undersigned, certify to the best of my knowledge that the patient/patient's legal representative signing this informed consent form had the study fully explained and clearly understands the nature, risks and benefits of his/her / his ward's / her ward's participation in the study.

_____ _____ _____
Name of Investigator Signature Date