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Reliability of Hand-Held Dynamometry for Measuring Force Production in People with Parkinson's Disease

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Abstract

Purpose: People with Parkinson's disease (PD) have impaired force production, which is associated with decreased mobility and falls risk. Reliable measurement of force production is important. Design: A repeated-measures, intra- and inter-rater reliability study was undertaken. Participants: 24 people with mild PD were measured by one or two raters. Outcome measures: Isometric force of the major upper and lower limb muscle groups was measured using hand-held dynamometry. Results: Fourteen participants were measured by the same rater on two occasions to determine intra-rater reliability. Ten participants were measured on two occasions by two different raters to determine inter-rater reliability. The intra-rater reliability of hand-held dynamometry was excellent in every muscle group, except the dorsiflexors. Intra-rater reliability was highest when measuring wrist extensors ($ICC_{(2,1)}$ = 0.98, 95% CI: 0.94 to 0.99) and lowest when measuring ankle dorsiflexors ($ICC_{(2,1)}$ = 0.87, 95% CI: 0.43 to 0.97). Inter-rater reliability was variable ranging from poor (wrist flexors: $ICC_{(2,2)}$ = -0.15, 95% CI: -1.14 to 0.60) to excellent (grip strength: $ICC_{(2,2)}$ = 0.97, 95% CI: 0.88 to 0.99). Conclusion: Hand-held dynamometry has good to excellent intra-rater reliability, but poor inter-rater reliability, for measuring force in the upper and lower limb in people with mild PD.

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ABSTRACT
Purpose: People with Parkinson's disease (PD) have impaired force production, which is associated with decreased mobility and falls risk. Reliable measurement of force production is important. **Design:** A repeated-measures, intra- and inter-rater reliability study was undertaken. **Participants**: 24 people with mild PD were measured by one or two raters. **Outcome measures**: Isometric force of the major upper and lower limb muscle groups was measured using hand-held dynamometry. **Results**: Fourteen participants were measured by the same rater on two occasions to determine intra-rater reliability. Ten participants were measured on two occasions by two different raters to determine inter-rater reliability. The intra-rater reliability of hand-held dynamometry was excellent in every muscle group, except the dorsiflexors. Intra-rater reliability was highest when measuring wrist extensors ($ICC_{(2,1)}$ = 0.98, 95% CI: 0.94 to 0.99) and lowest when measuring ankle dorsiflexors ($ICC_{(2,1)}$ = 0.87, 95% CI: 0.43 to 0.97). Inter-rater reliability was variable ranging from poor (wrist flexors: $ICC_{(2,2)}$ = -0.15, 95% CI: -1.14 to 0.60) to excellent (grip strength: $ICC_{(2,2)}$ = 0.97, 95% CI: 0.88 to 0.99). **Conclusion**: Hand-held dynamometry has good to excellent intra-rater reliability, but poor inter-rater reliability, for measuring force in the upper and lower limb in people with mild PD.

Key words: reproducibility of results, Parkinson's disease, muscle strength, muscle weakness, muscle strength dynamometer

INTRODUCTION

People with PD have many motor impairments including bradykinesia, balance impairment, tremor, and rigidity. It is also clear that people with PD have impaired force production in the lower limb muscle groups.[1,2] This loss of strength has been shown to contribute to activity limitations in people with PD. Canning et al reported that impaired force production in the knee extensors was correlated with reduced walking distance in a six-minute walk test.[3] Furthermore, impaired force production of the hip and knee extensors has also been shown to be correlated with poor standing up performance, and has increased the time taken to perform the timed up and go test, which is associated with increased falls risk in people with PD.[4,5,6] Therefore, interventions that may increase muscle strength are worth considering in people with PD.

Measuring force production is important for monitoring strengthening interventions in people with PD. However, in order to measure strength unconfounded by bradykinesia, force production needs to be measured isometrically. Some studies have found that isometric contractions can be measured reliably by a single rater in people with PD, however only a small number of muscle groups have been tested (n = 3; ankle dorsiflexors, hip abductors and grip).[7,8,9] It is clear that in healthy adults, the reliability of measuring force production varies across muscle groups, so it is important that all muscle groups are tested. Inter-rater reliability has only been examined for force production of the hand in people with PD. [10]

Hand-held dynamometry is a convenient, portable, and cheap option for measuring force production in the clinical setting in people with PD, however, the reliability of using hand-held dynamometry to measure force production in people with PD is unclear. Therefore, the research questions for this study were, in people with PD were

1. What is the intra-rater reliability of hand-held dynamometry for measuring the force production of all upper and lower limb muscle groups?
2. What is the inter-rater reliability of hand-held dynamometry for measuring the force production of all upper and lower limb muscle groups?

MATERIALS AND METHOD

Design

The intra-rater reliability of force production measured with a hand-held dynamometer was examined in 14 people with PD by two raters (rater 1 and 2) on 2 occasions, 30 minutes apart (Figure 1A). The inter-rater reliability was examined in 10 people with PD by two raters (rater 1 and 3) on 1 occasion each, 30 minutes apart (Figure 1B). The maximum force produced by 11 left and right upper limb and 12 left and right lower limb muscle groups were measured during isometric contractions. Muscle groups were measured in the same order across participants. 30 minutes rest has been shown to be enough to ensure valid measures of force production. [11] Measurements were conducted at the University Physiotherapy Clinic, during the "on" phase of medication. Different participants were measured to test for intra-rater reliability compared with inter-rater reliability. Ethical approval from the University Ethics Committee was obtained. All participants provided written informed consent.

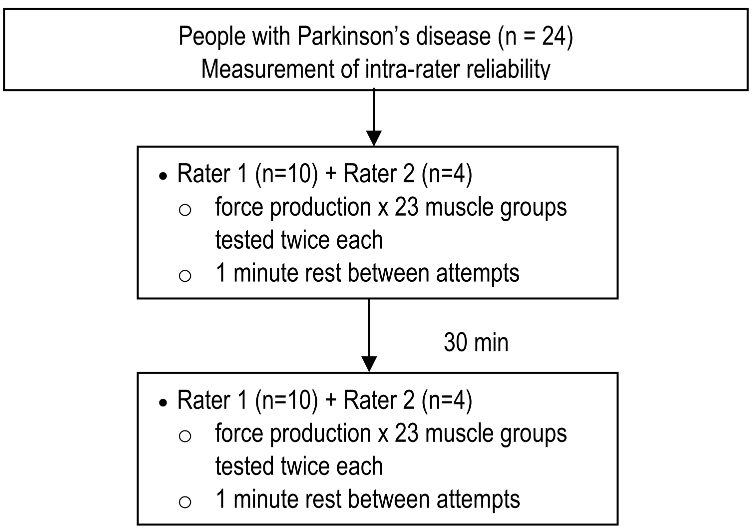

Figure 1A: Flow through the study/intra rater reliability

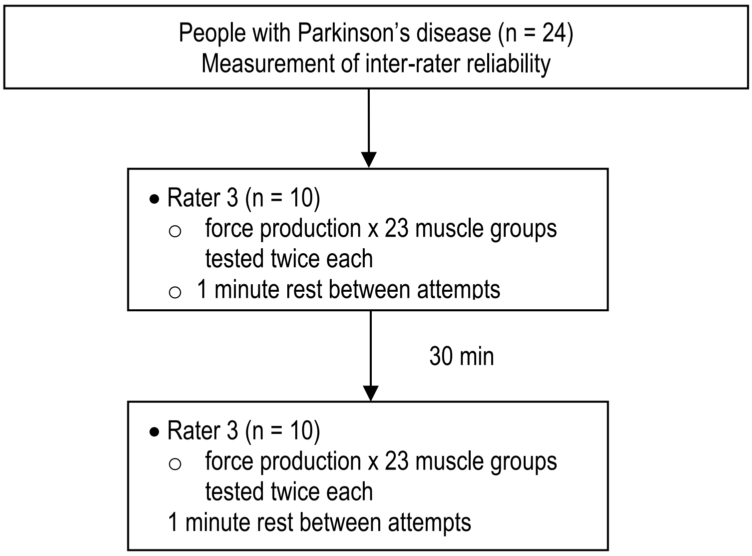

Figure 1B: Flow through the study/inter rater reliability

Participants

People with PD were recruited from a University Neurological Physiotherapy Clinic and were included in the study if they were over 40 years of age and had been diagnosed with idiopathic PD. Participants had to be able to walk independently with or without a mobility aid over 10 metres and been on stable levodopa medication. People with PD were excluded from the study if they if they scored 23 or less on the Mini-Mental State Examination, as this finding is indicative of mild cognitive impairment, which may have impacted a person's ability to follow testing instructions. Potential participants were also excluded if they had co-morbidities that were likely to impact on strength testing, e.g., previous stroke or joint replacements. [12,13,14]

Raters 1 and 2 were physiotherapy students with less than 6 months clinical experience. Rater 3 was an expert physiotherapist with over 15 years of clinical experience, largely in managing people with neurological conditions. Raters were trained in using hand-held dynamometers to measure force. Training included 30-minutes of practice using the hand-held dynamometer according to the measurement protocol on a person without Parkinson's disease. Raters completed measurement independently.

Measurement of Force

Muscle groups of the upper limb included shoulder flexors, extensors, abductors, adductors, internal rotators and external rotators, elbow flexors and extensors, wrist flexors and extensors, and hand grip. Muscle groups of the lower limb included: hip flexors, extensors, abductors, adductors, internal rotators and external rotators; knee flexors and extensors; and ankle plantar flexors, dorsiflexors, invertors and evertors. A wide, height-adjustable plinth was used to perform all measures other than hand grip strength (see supplementary material for full measurement protocol). Participants had two attempts at maximal force production for each muscle group, one minute apart. The best attempt was used to represent maximum voluntary contraction and the average force for the left and right side for each muscle group was used for data analysis. All muscle groups were measured using a DIGI-II dynamometer (Model 01163, Lafayette Instrument Inc., Indiana), except hand grip, which was measured using a hydraulic hand grip dynamometer, Model SH5003 (Saehan Corporation, Masan).

Data analysis

All data was analysed using SPSS version 26 (IBM Corp., New York). Intra-class correlation coefficient (ICC) was used to determine reliability. Intra-rater reliability was examined using a two-way mixed-effects model, single measurement, with absolute agreement. Inter-rater reliability was examined using a two-way random-effects model, a mean of 2 raters, with absolute agreement. Interpretation of ICCs was completed in accordance with Koo et al: less than 0.5 is considered poor reliability; between 0.5 and 0.75 is considered moderate reliability; values from 0.75 to 0.9 is considered good reliability; and values greater than 0.9 is considered excellent reliability. [15]

In addition to the ICC, the standard error of measurement (SEm) was calculated as standard deviation (SD) x √1-ICC, where SD is the SD of all scores from the participants across both testing occasions. Minimal detectable change (MDC, defined as the smallest change in force that can be detected by hand-held dynamometry beyond measurement error) was calculated as 1.96 x √2 x SEM. MDC% (MDC as a proportion of average force) was also calculated. [16]

RESULTS

Participant characteristics

There were 14 participants included in the study for intra-rater testing and 10 for inter-rater testing. Participant characteristics are in Table 1.

Table 1. Participant characteristics

Characteristic	Participants		
	All (n = 24)	Intra-rater (n = 14)	Inter-rater (n = 10)
Age (yr), mean (SD)	71 (8)	70 (8)	72 (8)
Sex, *n* male (%)	13 (54)	6 (43)	7 (70)
PD duration (yr), mean (SD)	5 (5)	7 (6)	3 (3)
Hoehn and Yahr stage (0-5), mean (SD)	1.8 (0.6)	2.0 (0.5)	1.6 (0.7)
Levadopa use, *n* yes (%)	22 (92)	10 (100)	12 (86)

Intra-rater Reliability

The intra-rater reliability of hand-held dynamometry for measuring force was excellent in every muscle group, except the dorsiflexors, which was good (Table 2). For the upper limb, intra-rater reliability was highest when force of the wrist extensors was measured using hand-held dynamometry ($ICC_{(2,1)}$ 0.98, 95% CI 0.94 to 0.99) and lowest when force of the shoulder internal rotators was measured ($ICC_{(2,1)}$ 0.96, 95% CI 0.70 to 0.99). In the lower limb, intra-rater reliability using hand-held dynamometry was highest when force of the ankle plantar flexors was measured ($ICC_{(2,1)}$ 0.98, 95% CI 0.93 to 0.99), and lowest when force of ankle dorsiflexors was measured ($ICC_{(2,1)}$ 0.87, 95% CI 0.43 to 0.97).

Table 2. Mean (SD) of force production (N) for each test, intra-class correlation coefficient (95% CI), SEm, MDC and MDC% for intra-rater reliability of hand-held dynamometry for measurement of maximal isometric force (n = 14)

Muscle group	Test 1 (Rater 1 & 2)	Test 2 (Rater 1&2)	$ICC_{(2,1)}$	SEm	MDC	MDC %
Shoulder Flexion	90 (32)	88 (37)	0.97 (0.87, 0.99)	6.7	19	21
Shoulder Extension	97 (43)	90 (47)	0.98 (0.90, 0.99)	6.2	17	18
Shoulder Abduction	90 (32)	82 (37)	0.96 (0.80, 0.99)	7.6	21	25
Shoulder Adduction	92 (49)	87 (48)	0.99 (0.96, 0.99)	4.7	13	15
Shoulder External Rotation	71 (33)	68 (33)	0.97 (0.90, 0.99)	6.4	18	25
Shoulder Internal Rotation	80 (35)	71 (26)	0.96 (0.70, 0.99)	6.1	17	22
Elbow Flexion	110 (50)	102 (40)	0.98 (0.89, 0.99)	6.2	17	16
Elbow Extension	96 (33)	94 (44)	0.96 (0.86, 0.99)	7.6	21	22
Wrist Flexion	70 (28)	63 (28)	0.98 (0.80, 0.99)	4.7	13	20
Wrist Extension	52 (25)	51 (24)	0.98 (0.94, 0.99)	4.1	11	22
Grip Strength	261 (66)	251 (72)	0.96 (0.84, 0.99)	11.7	32	13
Hip Flexion	97 (24)	100 (30)	0.91 (0.65, 0.98)	4.6	13	13
Hip Extension	88 (33)	90 (39)	0.97 (0.87, 0.99)	7.0	19	22
Hip Abduction	83 (21)	86 (18)	0.96 (0.83, 0.99)	6.6	18	21
Hip Adduction	91 (28)	87 (22)	0.92 (0.71, 0.98)	4.9	14	15
Hip External Rotation	63 (20)	60 (16)	0.95 (0.82, 0.99)	3.1	9	14
Hip Internal Rotation	58 (19)	60 (13)	0.96 (0.84, 0.99)	2.7	8	13
Knee Flexion	108 (49)	117 (52)	0.98 (0.88, 0.99)	8.6	24	21
Knee Extension	146 (51)	136 (40)	0.95 (0.80, 0.99)	10.0	28	20
Ankle Dorsiflexion	76 (26)	75 (16)	0.87 (0.43, 0.97)	5.2	14	19
Ankle Plantarflexion	84 (37)	86 (29)	0.98 (0.93, 0.99)	4.5	13	15
Ankle Eversion	57 (21)	56 (19)	0.95 (0.80, 0.99)	5.2	14	26
Ankle Inversion	56 (24)	57 (17)	0.93 (0.70, 0.98)	6.4	18	31

Sem = standard error of measurement, MDC = minimal detectable difference

Inter-rater Reliability

The inter-rater reliability of hand-held dynamometry for measuring force was variable ranging from poor to excellent (Table 3). For the upper limb, inter-rater reliability was highest when grip strength was measured ($ICC_{(2,2)}$ 0.97, 95% CI 0.88 to 0.99), suggesting an excellent level of agreement, and lowest when force of the wrist flexors was measured ($ICC_{(2,2)}$ -0.15, 95% CI -1.14 to 0.60). In the lower limb, inter-rater reliability was highest when force of the hip internal rotators was measured using hand-held dynamometry ($ICC_{(2,2)}$ 0.87, 95% CI 0.48 to 0.97). It was lowest when force of ankle plantar flexors was measured ($ICC_{(2,2)}$ 0.42, 95% CI -0.11 to 0.83).

Table 3. Mean (SD) of force production (N) for Rater 1 and Rater 3, intra-class correlation coefficient (95% CI), and Standard error of measurement (SEm) for inter-rater reliability of hand-held dynamometry for measurement of maximal isometric force (n = 10)

Muscle group	Test 1 Rater 1	Test 2 Rater 3	$ICC_{(2,2)}$ (95% CI)	SEm
Shoulder Flexion	86 (19)	93 (28)	0.87 (0.36, 0.97)	8.5
Shoulder Extension	90 (23)	93 (22)	0.84 (0.38, 0.96)	8.7
Shoulder Abduction	86 (21)	92 (29)	0.73 (-0.6, 0.93)	13.1
Shoulder Adduction	88 (23)	81 (27)	0.77 (0.11, 0.94)	11.9
Shoulder External Rotation	70 (19)	75 (20)	0.79 (0.07, 0.95)	8.9
Shoulder Internal Rotation	82 (27)	92 (24)	0.66 (0.27, 0.92)	14.9
Elbow Flexion	110 (36)	134 (37)	0.34 (0.30, 0.78)	30.7
Elbow Extension	88 (29)	101 (22)	0.36 (-0.40, 0.80)	20.6
Wrist Flexion	66 (16)	84 (24)	-0.15 (-1.14, 0.60)	23.4
Wrist Extension	55 (18)	67 (13)	0.14 (-0.54, 0.69)	15.3
Grip Strength	237 (68)	244 (60)	0.97 (0.88, 0.99)	10.9
Hip Flexion	103 (24)	127 (28)	0.60 (-0.27, 0.90)	18.0
Hip Extension	95 (28)	92 (20)	0.45 (-1.7, 0.87)	17.7
Hip Abduction	82 (15)	85 (18)	0.74 (-0.16, 0.94)	8.2
Hip Adduction	88 (16)	96 (21)	0.84 (0.36, 0.96)	7.5
Hip External Rotation	61 (13)	66 (14)	0.68 (-0.26, 0.93)	7.7
Hip Internal Rotation	59 (14)	60 (21)	0.87 (0.48, 0.97)	6.2
Knee Flexion	101 (28)	108 (28)	0.84 (-0.14, 0.97)	11.1
Knee Extension	132 (34)	168 (41)	0.57 (-0.26, 0.89)	26.9
Ankle Dorsiflexion	88 (28)	101 (22)	0.52 (-0.25, 0.88)	18.0
Ankle Plantarflexion	89 (22)	125 (29)	0.42 (-0.11, 0.83)	23.6
Ankle Eversion	68 (21)	67 (21)	0.74 (0.56, 0.93)	10.5
Ankle Inversion	62 (21)	68 (21)	0.58 (-0.27, 0.89)	13.5

Minimal Detectable Change

The MDC for measurements taken by the same rater was, on average, 17 N (SD 6), and the MDC% on average was 20% (SD 5). MDC ranged from 8 N (hip internal rotators) to 33 N (grip), and MDC% ranged from 13% (hip internal rotators and grip) to 31% (ankle inversion).

DISCUSSION

This study examined the intra- and inter-rater reliability of hand-held dynamometry for measuring force production in 23 different muscle groups in people with mild PD. Hand-held dynamometry had excellent intra-rater reliability for all upper and lower limb muscle groups, with the exception of the dorsiflexors, which had good intra-rater reliability. However, the minimal detectable change was relatively large, with a change of around 20% in force required to be certain the change was not due to measurement error. Inter-rater reliability of hand-held dynamometry was lower than intra-rater reliability. Inter-rater reliability was excellent when measuring grip strength, good for shoulder flexors, extensors, adductors and external rotators, hip adductors and internal rotators and the knee flexors, but moderate or poor for the remaining muscle groups.

There was considerable variation *between* examiners in measuring force production for all muscle groups, except grip strength. This suggests that measurements may not be valid when different examiners use hand-held dynamometry for people with PD. Strength of examiners influences inter-rater reliability of isometric force testing, because the examiner must match the force produced by the participant.[17,18] Wikholm and Bohannon demonstrated that inter-rater reliability was higher for muscle groups that produce lower force and lower for muscle groups that produce mean force above 120 Newtons.[18] In our study, an average force production of greater than 120 Newtons was recorded in the elbow flexors, hip flexors, knee extensors, and plantar flexors, so it is possible that examiner strength was a confounding factor.

Given measurement of hand grip strength had excellent inter-rater reliability, a post-hoc analysis was performed to examine the relationship between hand grip strength and force production of other upper limb muscle groups (Table 4). A strong correlation was found between hand grip strength and the force production of all upper limb muscle groups. Therefore, hand grip strength could be used as a proxy of force production for the upper limb in people with PD when measurements are required over time and a single examiner is not feasible. The minimal detectable change for hand grip, when using two examiners, was 30 N (13% change). As such, clinicians should ensure a change of at least this size to be sure of a real change in force production, and not measurement error.

Table 4 Correlation (r) and significance (p) between hand grip strength and force of UL muscle groups.

Muscle group	r (p)
Shoulder External Rotation	0.86 (0.001)
Elbow Flexion	0.86 (0.001)
Wrist Extension	0.84 (0.002)
Shoulder Adduction	0.82 (0.004)
Shoulder Internal Rotation	0.82 (0.004)
Shoulder Abduction	0.80 (0.005)
Wrist Flexion	0.78 (0.008)
Shoulder Extension	0.78 (0.008)
Elbow Extension	0.78 (0.008)
Knee Flexion	0.78 (0.007)
Shoulder Flexion	0.76 (0.01)

Limitations

This study has some limitations. During inter-rater reliability testing, the order of examiners was not randomised. However, the maximum force recorded was only larger on the first test compared with the second 70% of the time. Furthermore, only two examiners were included, which may lead to an underestimate of the reliability of the measure, particularly since there was a substantial difference in the experience of the two examiners.[15] Finally, for both intra- and inter-rater reliability testing, the sample was small and participants had mild PD. Both the size and homogeneity of the sample can result in underestimating the reliability of the measure.[19] As such, the findings should be interpreted with caution.

CONCLUSION

Hand-held dynamometry has good to excellent intra-rater reliability for measuring force production in a wide range of muscle groups in the upper and lower limb in people with mild PD, although the minimal detectable change on average was 20%. In contrast, inter-rater reliability was mostly moderate or poor, except for hand grip strength which was performed by a device that participants use without physical input by the examiner. As such, given hand-held dynamometry is a convenient, portable and cheap option for measuring force production, it can be used in the clinic in people with mild PD, as long as measurements taken over time are done so by a single examiner to ensure reliability. Alternatively, given grip strength is correlated with force production of all other upper limb muscle groups, it could be used as a proxy in cases where a single examiner is not feasible.

REFERENCES

1. Skinner JW, Christou EA, Hass CJ. Lower Extremity Muscle Strength and Force Variability in Persons With Parkinson Disease. *Journal of neurologic physical therapy : JNPT.* 2019;43(1):56-62.
2. Salmon S, Preston E, Mahendran N, Flynn A, Ada L. People with mild PD have impaired force production in all lower limb muscle groups: A cross-sectional study. *Physiotherapy research international : the journal for researchers and clinicians in physical therapy.* 2021;26(2):e1897.
3. Canning CG, Ada L, Johnson JJ, McWhirter S. Walking capacity in mild to moderate Parkinson's disease. *Archives of Physical Medicine and Rehabilitation.* 2006 Mar;87(3):371-375.
4. Inkster LM, Eng JJ, MacIntyre DL, Stoessl AJ. Leg muscle strength is reduced in PD and relates to the ability to rise from a chair. *Movement disorders.* 2003 Feb;18(2):157-162.
5. Pääsuke M, Mõttus K, Ereline J, Gapeyeva H, Taba P. Lower limb performance in older female patients with Parkinson's disease. *Aging clinical and experimental research.* 2002 Jun;14(3):185-191.
6. Mak MK, Pang MY. Balance confidence and functional mobility are independently associated with falls in people with Parkinson's disease. *Journal of neurology.* 2009 May;256(5):742-749.
7. Allen NE, Canning, C. G., Sherrington, C., & Fung, V. S. Bradykinesia, muscle weakness and reduced muscle power in Parkinson's disease. *Movement Disorders.* 2009;24(9): 1344-1351.
8. Purser JL, Pieper CF, Duncan PW, et al. Reliability of physical performance tests in four different randomized clinical trials. *Archives of physical medicine and rehabilitation.* 1999 May;80(5):557-561.

9. Schenkman M, Cutson TM, Kuchibhatla M, Chandler J, Pieper C. Reliability of impairment and physical performance measures for persons with Parkinson's disease. *Physical therapy.* 1997 Jan;77(1):19-27.
10. Chamorro C, Armijo-Olivo S, De la Fuente C, Fuentes J, Javier Chirosa L. Absolute Reliability and Concurrent Validity of Hand Held Dynamometry and Isokinetic Dynamometry in the Hip, Knee and Ankle Joint: Systematic Review and Meta-analysis. *Open Med (Wars).* 2017;12:359-375.
11. Kolber MJ, Beekhuizen K, Cheng MS, Fiebert IM. The reliability of hand-held dynamometry in measuring isometric strength of the shoulder internal and external rotator musculature using a stabilization device. *Physiotherapy theory and practice.* 2007;23(2):119-124.
12. Dorsch S, Ada L, Canning CG. Lower limb strength is significantly impaired in all muscle groups in ambulatory people with chronic stroke: a cross-sectional study. *Archives of Physical Medicine and Rehabilitation.* 2016 Apr;97(4):522-527.
13. Mitchell AJ. A meta-analysis of the accuracy of the mini-mental state examination in the detection of dementia and mild cognitive impairment. *Journal of Psychiatric Research.* 2009 Jan;43(4):411-431.
14. Cavanellas NT, Cossich VR, Nicoliche EB, Martins MB, de Sousa EB, Salles JI. Comparative analysis of quadriceps and hamstrings strength in knee osteoarthritis before and after total knee arthroplasty: a cross-sectional study. *Revista Brasileira de Ortopedia.* 2018 Feb 23;53(2):158-164.
15. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of chiropractic medicine.* 2016 Jun;15(2):155-163.
16. de Vet HC, Terwee CB. The minimal detectable change should not replace the minimal important difference. *Journal of clinical epidemiology.* 2010;63(7):804-805; author reply 806.
17. Thorborg K, Bandholm T, Schick M, Jensen J, Hölmich P. Hip strength assessment using handheld dynamometry is subject to intertester bias when testers are of different sex and strength. *Scandinavian journal of medicine & science in sports.* 2013;23(4):487-493.
18. Wikholm JB, Bohannon RW. Hand-held dynamometer measurements: tester strength makes a difference. *Journal of Orthopaedic & Sports Physical Therapy.* 1991 Apr;13(4):191-198.
19. Springate SD. The effect of sample size and bias on the reliability of estimates of error: a comparative study of Dahlberg's formula. *European Journal of Orthodontics.* 2011;34(2):158-163.

APPENDIX 1: Testing Positions for all Muscle Groups

Muscle group	Position of limb*	Placement of dynamometer	Stabilisation
Shoulder flexors	Shoulder at neutral and elbow extended	Just proximal to epicondyles of humerus	None
Shoulder extensors	Shoulder flexed so that elbow is just off the plinth and elbow flexed to 90°	Just proximal to epicondyles of humerus	None
Shoulder abductors	Shoulder abducted to 45° and elbow flexed to 90°	Just proximal to lateral epicondyle of humerus	None
Shoulder adductors	Shoulder abducted to 45° and elbow flexed to 90°	Just proximal to medial epicondyle of humerus	None
Shoulder external rotators	Shoulder abducted to 45° and elbow at 90°	Just proximal to styloid process of ulna	Medial aspect of elbow
Shoulder internal rotators	Shoulder abducted to 45° and elbow at 90°	Just proximal to styloid process of ulna	Lateral aspect of elbow
Elbow flexors	Shoulder at neutral, elbow flexed to 90° and forearm supinated	Just proximal to styloid process of ulna	None
Elbow extensors	Shoulder at neutral, elbow flexed to 90° and forearm in neutral	Just proximal to lateral styloid process of ulna	None

Wrist extensors	Shoulder at neutral, elbow flexed to 90°, wrist at neutral and fingers relaxed	Just proximal to metacarpophalangeal joints	Distal forearm
Wrist flexors	Shoulder at neutral, elbow flexed to 90°, wrist at neutral and fingers relaxed	Just proximal to metacarpophalangeal joints	Distal forearm
Grip strength	Shoulder at neutral, elbow flexed to 90°, wrist at neutral and fingers grasped around dynamometer	In participant's grasp	None
Hip flexors	Hips and knees flexed to 90° with lower legs up on box	Just proximal to femoral condyles	None
Hip extensors	Hip at 0° flexion, ipsilateral knee flexed to 90° and hanging off side of plinth, contralateral limb in neutral on plinth	Just proximal to femoral condyles	None
Hip abductors	Hip and knee at neutral, contralateral knee flexed to 90° and hanging off side of plinth	Just proximal to lateral femoral condyle	None
Hip adductors	Hip and knee at neutral, contralateral knee flexed to 90° and hanging off side of plinth	Just proximal to medial femoral condyle	None
Hip internal rotators	Hips and knees flexed to 90° with lower legs up on box	Just proximal to lateral malleolus	Medial aspect of knee
Hip external rotators	Hips and knees flexed to 90° with lower legs up on box	Just proximal to medial malleolus	Lateral aspect of knee
Knee flexors	Hips and knees flexed to 90° with lower legs up on box	Just proximal to malleoli	None
Knee extensors	Hips and knees flexed to 90° with lower legs up on box	Just proximal to malleoli	None
Ankle dorsiflexors	Hips and knees flexed to 90° with lower legs up on box, ankle at plantargrade	Just proximal to metatarsophalangeal joints	None
Ankle plantar flexors	Hips and knees flexed to 90° with lower legs up on box, ankle at plantargrade	Just proximal to metatarsophalangeal joints	None
Ankle invertors	Hips and knees flexed to 90° with lower legs up on box, ankle at plantargrade	Just proximal to 1st metatarsophalangeal joint	Just proximal to malleoli
Ankle evertors	Hips and knees flexed to 90° with lower legs up on box, ankle at plantargrade	Just proximal to 5th metatarsophalangeal joint	Just proximal to malleoli