Title: Assessing Muscle Strength for the purpose of Classification in Paralympic Athletics: a review and recommendations

Author: Emma Beckman Mark Connick Sean Tweedy

PII: S1440-2440(16)30153-0
DOI: http://dx.doi.org/doi:10.1016/j.jsams.2016.08.010
Reference: JSAMS 1370

To appear in: *Journal of Science and Medicine in Sport*

Received date: 9-7-2015
Revised date: 27-6-2016
Accepted date: 18-8-2016

Assessing Muscle Strength for the purpose of Classification in Paralympic Athletics: a review and recommendations

Emma Beckman[1], Mark Connick[1] and Sean Tweedy[1]

[1] School of Human Movement and Nutrition Sciences, University of Queensland

Blair Dr, University of Queensland, Brisbane, Australia 4072

Corresponding Author:

Emma Beckman, PhD

T: +61 7 33467904

E: e.beckman@uq.edu.au

Word count (excluding abstract and references): 3989

Abstract word count: 202

Number of Tables: 1

Number of Figures: 1

Assessing Muscle Strength for the purpose of Classification in Paralympic Sport: a review and recommendations

Word count (excluding abstract and references): 3989

Abstract word count: 202

Number of Tables: 1

Number of Figures: 1

Abstract

Classification in Paralympic Sport aims to minimize the impact of 10 eligible types of impairment on the outcome of competition. Methods for assessing the extent to which a given body structure or function has been impaired are required, but are challenging because it is not possible to directly measure an absence or loss. Rather, impairment must be inferred by measurement of extant body structures or functions. This manuscript reviews the literature concerning the assessment of strength with the aim of identifying and describing the most appropriate method for inferring strength impairment in para-athletes. It is posited that the most appropriate voluntary strength assessment method for inferring strength loss in para-athletes will be multi-joint, isometric tests performed at joint angles that facilitate maximum force production. Evidence suggests such methods will permit development of tests that are specific to a variety of para-sports and which are reliable, ratio-scaled, and resistant to training. Future research should: develop sport-specific tests which are suitable for assessment of athletes with strength impairments of variable severity and distribution; and scientifically evaluate the extent to which such tests permit strength impairment to be validly inferred, including specific evaluation of the extent to which such measures respond to athletic training.

Keywords: Athletic performance, muscle strength, impairment, track and field

Introduction

There are 27 Paralympic sports – 22 summer sports and five winter sports – and each of these sports has its own sport-specific classification system for impairments. The purpose of classification is to promote participation in sport by people with disabilities by minimising the impact of eligible impairments on the outcome of competition[1]. There are ten eligible impairment types in Paralympic Sport; intellectual, visual, impaired passive range of motion, impaired strength, ataxia, athetosis, hypertonia, short stature, leg length discrepancy and limb deficiency: the impairment on which this paper focuses is impaired strength. Paralympic classification systems aim to ensure that athletes who succeed in Paralympic sport do so because they have the most favorable combination of anthropometric, physiological, and psychological attributes and have enhanced them to best effect through training[1]. The corollary of this aim is that athletes should not succeed in Paralympic sport simply because they have an impairment that causes less activity limitation than their competitors.

The IPC Classification Code mandated the development of evidence-based classification in all Paralympic Sports, [2] and subsequently the IPC Position Stand on Classification in Paralympic Sport detailed the scientific principles for achieving evidence-based classification. The language used in the Code and the Position Stand is consistent with the International Classification of Functioning, Disability and Health and key terms are presented in Table 1[3]. The interrelationship between these terms can be illustrated using the example of myelomeningocele, which is a health condition that is characterised by impairment of the spinal column and cord (body structures), and therefore impairments of muscular strength (body function), typically in the lower limbs. These impairments have a negative impact on the execution of activities such as walking, running and swimming referred to as activity limitations. The extent of activity limitation that results from a given impairment is determined by two things: the activity the person wishes to do (for example, a given loss of strength in the legs may cause relatively more activity limitation in running than in swimming); as well as the muscles affected (location of the impairment) and the extent to which voluntary force production is reduced (severity of the impairment).

Conceptually, evidence-based Paralympic classification requires methods that permit quantification of the extent of activity limitation that results from an impairment[4], so that if an athlete with myelomeningocele wished to compete in the 50m freestyle, their impairment could be assessed in a way that permitted them to be placed in a class for athletes with impairments that caused an approximately equivalent amount of activity limitation. The aim of this paper is to review the scientific literature to identify the most appropriate method of strength assessment for this purpose.

Assessing strength impairment for Paralympic classification

From the outset it is important to recognise that the term “assessing” impairment is not synonymous with “measuring” impairment because, of course, it is not possible to directly measure a loss or absence. Rather, in order to assess the extent to which a particular body structure or function has been impaired, extant body structures or functions must be measured and the results used to infer impairment. To illustrate, in order to assess the length of lower leg lost by a bilateral, trans-tibial amputee it is not possible to directly measure the absence. However principles of body proportionality permit the loss to be inferred based on direct measurement of the length of other body segments (e.g., thigh, upper arm and forearm) and recommendations for applying these principles for the purposes of Paralympic Classification have recently been described[5].

In the case of strength, the process of inferring impairment or loss is challenging but vital to address because it a fundamental component of classification in 16 Paralympic of the 27 Paralympic sports. The most valid assessment to infer loss would require a suitable pre-morbid measure of strength prior to a person's injury and this would then be compared to strength remaining after injury following appropriate rehabilitation. However this gold-standard assessment is rarely available and therefore the best method for inferring loss depends on assessing extant strength of each individual. The consideration of what is measured should always be taken into context however, as if a person is measured after they were injured but before any considerable athletic training has taken place than the measure would be capturing loss of strength from both impairment and disuse and sedentary behavior.

Broad principles for a valid method of assessing impairment for the purposes of Paralympic classification have previously been published, these being that methods must be: objective; reliable; precise; ratio-scaled; measure only the specified body structure or function (i.e. strength); be as training resistant as possible and parsimonious [1,6]. These criteria for a test of impairment have been based on well-accepted theory; however, the scientific literature that underpins the rationale for these criteria and translates it to the practical development of tests has not been explored, making this review an important step towards identifying tests that can be used to infer how much strength has been impaired.

General Criteria for measures used to assess impairment

The concept of reliability and validity of measurement tools in exercise science is well known. Reliable and valid outcome measures that are ratio scaled are also necessary to allow the application of inferential statistics such as regression that will enable the quantification of the relationship between impairment and performance, a key requirement of evidence-based classification[1].

It is important to consider in Paralympic Sport that athletes may present with health conditions and disabilities that result in the presence of more than one impairment, for example they may experience loss of strength and loss of range of motion and both may affect their sports performance. Therefore, measures should be specific to the condition of interest, for example in the case of impaired strength, the measure should only reflect strength and be minimally influenced by the presence of other impairments, such as impaired balance or range of movement[1]. This is to ensure the accurate quantification of the relationship between the impairment of interest and performance without the confounding influence of other impairment types during the classification process.

The importance of selecting measures that are as training resistant as possible is a key feature of developing methods of assessing impairment in Paralympic Sport. It is imperative that the methods used to infer loss in the process of classification facilitate the development of a selective classification system [1]. This means that impairment is used to place athletes into groups to ensure that an athlete whose preparation is optimal improves their chances at success during competition. The alternative is a performance-based system, where training can result in movement between classes, for example, handicapping in golf or higher competition grades in football. If athletes were to train effectively and this resulted in class movement, this would be an anathema to Paralympic Sport. This underlying need to ensure classification processes reflect the aims and ideals of the Paralympic movement mean that methods of assessing strength impairment must be as training resistant as possible.

Strength training responses in people with impaired strength

The task of assessing the extent to which a body structure or function has been impaired is simplified in some cases as measures used to infer impairment are not training responsive. For example, in limb deficiency (such as dysmelia, and amputation) there is no risk of training impacting on the assessment process. When there is a loss of muscle strength in the presence of a complete spinal cord injury, there is also no confounding influence of training- no amount of training will impact on the muscle function available below the level of a motor-complete lesion with studies showing significant and continuous declines in muscle mass after injury[7]. However, there are a number of health conditions that cause impairments to muscle strength where the assessment of strength may be impacted by athletic training[8-11].

While most of the available literature is not specifically on athletic populations, studies have shown increases in muscle strength in patients with permanent musculoskeletal impairment following resistance training including polio, cerebral palsy and stroke.[8-16]. In a study in patients with post-polio muscle atrophy, after progressive strength training, an increase in dynamic strength of the upper and lower limbs was observed but there was no corresponding increase in isometric strength or in muscle size[11]. The authors suggest this was a result of strength gains arising from neural adaptations, as perhaps in this population the remaining innervated fibers had already undergone maximal hypertrophy post injury.

Improvements to muscle strength after resistance training in individuals with cerebral palsy[14,17,18] have been shown, although more literature is suggesting activity limitations in this population are likely to result from coordination difficulties or as a result of impaired rate of force development, rather than maximal force production [19,20]. There is considerable research with stroke patients, with strength training demonstrated to be effective to increase muscle strength and decrease activity limitations experience by stroke survivors. [21-23]

This body of literature suggests that the measurement of strength may be influenced by training, even in the presence of pathologically impaired strength. It is likely to vary as a function of the method of strength assessment used to detect changes in muscle strength and this literature therefore emphasizes the need to determine the best method of strength assessment for the process of inferring loss in classification.

Methods available to evaluate strength impairment

The modes of assessment of impairment available include manual muscle testing (the mode currently used in Paralympic Classification), as well as the three most commonly used to assess strength in the sports sciences and rehabilitation literature –isotonic, isokinetic or isometric measures[24].

Currently, strength is assessed in classification using Manual Muscle Testing (MMT) techniques[25,26]. For the purpose of inferring strength impairment it has a number of desirable qualities (easy to administer, widely utilized in clinical practice, inexpensive), however its main advantage for use in classification is that the outcome is based on the loss of normal function. Individuals are rated on whether they can produce what is termed as "normal" resistance (muscle grade of 5). Despite this conceptual advantage for inferring loss, MMT has several important disadvantages which make it unsuitable as a method of strength assessment for use in evidence-based classification systems. Firstly, while the methods provide valuable clinical information, their application for scientific purposes is problematic because acceptable inter-rater reliability is extremely difficult to achieve in people with neuromusculoskeletal impairments[27,28]. Achieving acceptable interrater reliability for measures of impairment is a particular challenge in Paralympic sport because they must be applied internationally by culturally diverse classifiers. Secondly MMT methods use ordinal scales which are unsuitable for research which aims to develop evidence-based methods of classification as they don't allow the use of inferential statistics[29].

With MMT shown to be unsuitable, the options of isometric, isotonic and isokinetic should be explored. There are two key factors that may be examined in the literature to determine the suitability of the different modes, primarily related to the assessment of maximum force generating capacity and the specificity of the measures to athletic performance.

Strength is defined as the force generated by the contraction of a muscle[3]. This must be assessed maximally in classification in order for loss of strength to be inferred. The maximal voluntary force generating capacity of a muscle is traditionally assessed in isometric contractions, predominantly due to the fundamental property of muscles that dictates that maximal force occurs at a velocity of zero[30]. Once movement is initiated, force production can be interpreted as submaximal and a function of the velocity of the movement[30]. Early EMG studies confirm the importance of isometric contractions in assessing maximal muscle force and there is substantial evidence showing a relationship between the force generated during isometric contractions and muscle activation (i.e., EMG is linearly proportional to muscle contractile force). This is important because in order to get maximum voluntary isometric force, the muscle(s) needs to maximally activated (voluntarily)[31,32]. The same is not true in isotonic contractions because other factors such as muscle length play a role in the force generated[30]. Therefore to obtain an estimate of how much the muscles can be voluntarily activated, isometric strength measures are the most useful. It must be considered that in athletes with neuromusculoskeletal impairments, the voluntary activation levels in isometric measures may be impaired, with some research suggesting this may be by up to 50%, and has been demonstrated in cerebral palsy, stroke and multiple sclerosis. Whie the evidence in not available in impaired populations, literature has shown that resistance training may improve maximum activation levels in non-disabled individuals[33], so while it is unlikely to be feasible to assess activation deficits in the classification process, considerations for trainability of isometric measures developed for the purpose of classification must be taken into account in future research.

The second factor that may assist in the determination of the most useful measurement mode relates to training interventions and specificity. The principles of specificity suggest that the stronger the relationship that is shown between a measure and a performance outcome, the more relevant it is to reflect changes in strength that occurs with training[24] and this has been a focus of considerable literature in non-disabled athletes. To be valid for inferring loss in classification however; measures should be as training resistant as possible, therefore the literature which has shown a weak relationship between strength modes and athletic performance would be the most useful for the purpose of classification.

In the absence of literature specific to para-athletes, the non-disabled sport science literature has consistently shown strong relationships between various isotonic tests and athletic performance than any other mode. Mahler found a correlation of 0.89 between isotonic tests and sprint performance[34] and Murphy found a correlation of 0.86 between isotonic tests (bench press) and seated shot put performance[35]. Studies that have examined isokinetic strength and performance have been varied with some researchers finding strong correlations (r=0.93) for isokinetic knee extension assessment and sprint performance[24] and others finding only moderate correlations between isokinetic knee extension and sprint speed[36]. Some have found no significant correlations between isokinetic assessment (knee flexion and extension) and sprint performance[37,38] and researchers have indicated that test velocity plays a significant role in these discrepancies.

Studies investigating isometric strength and performance have shown weak but significant correlations between isometric strength and throwing performance (r= 0.11 to 0.55) [39] as well as similarly poor relationships between isometric strength and sprint performance[40,41].

Kollock demonstrated a highly variable relationship between isometric single joint strength and functional performance on sports-related tasks such as hopping[42]. This body of literature suggests that isotonic and isokinetic tests consistently show stronger relationships to performance than isometric tests and in an athletic context are therefore likely to be more training responsive and less appropriate for classification. This has yet to be fully explored in athletes with disabilities and should be a focus of future research.

Training literature also contributes, with research showing that training 1RM squats improved strength of a 1RM squat by nearly 75% after 8 weeks, however training with an isometric leg press only increased 1RM squat strength by 25% following the 8 week training period[43] and there are similar studies noting that strength training induced changes in weight lifting strength may be unrelated to changes in isometric strength[44]. Sale et al reported that 19 weeks of isotonic training three times a week increased 1RM leg press strength by 29% but isometric knee extension strength did not significantly change[45]. These studies indicate the training resistance of isometric measures and suggest that isometric methods of assessment may prove useful in classification, provided research is able to determine similar outcomes in athletes with impairments. It will be of great importance to ensure this research is performed across the spectrum of impairment as the potential trainability of isometric outcome measures may relate to the severity of the impairment in addition to the presence of multiple impairment types.

Enhancing validity through specificity of strength assessment

The literature indicates that isometric tests appear to have the most validity for the purpose of inferring loss of muscle strength in Paralympic classification, given they appear to be the most training resistant of the modes and accurately assess maximum force generating capacity of the muscle. The development of further characteristics of tests that may be valid for use in classification should reflect other key criteria in assessing impairment, including the need for tests that are relevant for performance. Features that may enhance the specificity of isometric tests to allow more of the variance in performance to be explained were identified and reviewed including; the selection of joints involved in a test, the number of joints involved, the joint position employed, and the outcome variables selected for use in an isometric test.

Determination of Joints involved

Ensuring specificity in the development of tests for classification is imperative, for example; elbow extension strength will impact wheelchair racing performance but ankle strength will not, however if the activity of interest is running this example is then reversed. To develop tests of strength impairment, the biomechanical (strength) determinants of athletic performance should be clearly identified and tests developed for different events that reflect these determinants. This is a well-known concept in sport science, where biomechanists and coaches strive to identify key factors that will optimize performance, some key examples of this are presented in a review of Paralympic sport research needs in biomechanics [46]. In the context of classification it is essential that the key muscle groups or joints for performance of an activity are identified and subsequently assessed in a strength test battery to ensure that the tests are relevant to the activity of interest.

Number of joints involved in test

Research has indicated that strength methods that use single joint assessments have a weaker relationship with functionality[24]. While traditionally, isometric and isokinetic activities utilize less joint involvement than isotonic tests, both can be implemented using multi-joint procedures. Isometric tests using multiple joints have been shown to have stronger relationships to athletic performance[47], especially when the most specific positions are used and the muscles contributing to the force production are representative of the activity of interest[48,49]. Multi-joint tests will enhance the variance in performance that is explained by the measures, enhancing the validity of the tests for use in classification[6].

Joint Position

Isometric strength assessment varies considerably as a function of joint angle. Murphy and colleagues showed a higher peak force during an isometric bench press at an elbow angle of 120 degrees compared to an elbow angle of 90 degrees[50]. As the bench press is a multi-joint activity the difference here may also be explained by differences in joint moment arms, not simply muscle length[51]. Similarly, in the lower body, studies have shown total leg extension strength to be higher at a knee angle of 120 degrees than 90 degrees[52]. It is unknown whether varying presentations of impairments will impact on the expression of maximum isometric force at different joint angles in para-athletes, however until more research is performed, the principles behind joint position in non-disabled athletes should be applied.

Research has shown that joint angle may also impact the relationship of the strength measure to athletic performance. Murphy and colleagues showed that while peak force in a maximum voluntary contraction (MVC) could be generated in an isometric contraction similar to a bench press activity at an elbow angle of 120 degrees, the relationship between the isometric strength and bench press performance was much higher when the elbow angle was 90 degrees[50]. The authors suggested this may be a result of differences in motor unit recruitment patterns and differing muscle mechanics at varying joint angles[50] and is a consideration when designing protocols that explain maximum variance in athletic performance. This literature indicates the importance of standardized positions when implementing isometric protocols in a classification context, given the significant impact of joint angle. From a classification perspective, the imperative to measure maximum force production capabilities is of the utmost importance and therefore joint positions should be established based on maximum force, however the position chosen should be within the joint angles used in the sport of interest, to enhance specificity.

Outcome measures of isometric assessment

Outcome variables used in the literature of isometric strength protocols report maximum voluntary contraction force (MVC) and/or the rate of force development (RFD) achieved during the test. A maximum voluntary contraction (MVC) may be obtained through isometric protocols that apply force gradually or alternatively, as rapidly as possible, with the difference in these measures impacting on the outcome variable of rate of force development (RFD). For classification purposes, the key outcome measure required is the MVC value and the literature has varied as to whether this value is significantly different depending on the instructions used during testing[53,54]. A more relevant question to indicate the importance of MVC protocols in classification relates to the relative validity of the measure to performance. Studies have shown stronger relationships between isometric strength and athletic performance when the relationship between performance and RFD has been assessed, as compared to MVC [55,56]. Viitasalo and Aura reporting a very strong correlation (r=0.9) for an isometric leg extension test with rapid force generation when RFD was compared to vertical jump height[55] . West and colleagues showed that when isometric peak MVC is compared to dynamic performance, relationships are weaker, however when force-time data is used it shows a stronger relationship to dynamic performance[57]. Literature suggests that this is because force time characteristics of isometric strength are more reflective of neuromuscular adaptations that may correlate better with dynamic performance than isometric peak force. This literature suggests that MVC should be the outcome measure of interest in isometric tests for the purpose of classification rather than RFD given that measures that have a stronger relationship to athletic performance are likely to also be more training responsive.

Given that the RFD outcome is not required and the literature has shown inconsistencies related to whether fast or slow force application results in higher MVC's, participant instructions in isometric strength tests for classification should encourage a slow to moderate build-up of force to maximum during the test. Studies have suggested verbal encouragement can considerably improve MVC results and should be included in the protocol[58].

Recommendations

A systematic approach to selecting strength assessment methods for use in classification is required. Valid measures of inferring loss of strength in classification should measure maximal force generating capacity and be as training-resistant as possible, therefore the literature indicates that the development of isometric tests will be the most valid for this purpose.

To ensure the validity of the isometric protocols, steps should be taken to improve the sport specificity of the test battery to athletic performance. The principal muscle groups used in the event or sport of interest must therefore be identified. The synthesis of the literature also suggests that isometric tests should be performed in multi-joint positions at standardised joint angles that are allow maximum force production in with instructions given to participants to develop force slowly as these characteristics will ensure elements of specificity are addressed. Additionally, the outcome of MVC should be used for analysis and tests should be conducted with strong verbal encouragement by testers.

Future research is imperative to develop and evaluate such test batteries on athletes with disabilities, however there is promising evidence in the literature on non-disabled athletes that suggests that test batteries developed in this way may suit the criteria for a test of impairment[59]. A study on wheelchair athletes has also indicated that these principles would hold in athletes with impairments, with a study by Turbanski and Schmidtbleicher showing improvements to both isometric and isotonic strength after 8 weeks of heavy strength training but a greater percent change was shown in dynamic activities when compared with the isometric multi-joint test[60]. An example of a test developed for running events might be one such as presented in Figure 1, an isometric test where force is applied in a standardized position to a force transducer, simultaneously assessing, hip and knee extension (known to be determinants of running performance)[41] in a position that is maximizing force production in a range of motion that is utlised during the running action.

Research is required to develop and evaluate tests with these features and determine their reliability, as well as their relationship to athletic performance in athletes with disabilities to determine the impact of impairment on activity limitation. Importantly, research is also required that assesses the response of these measures to athletic training, as despite the intent being to develop tests that are training resistant, quantifying the degree of training response would further validate the use of these tests in the classification process. This important consideration needs to incorporate study samples that include variance in impairment severity as the classification process will be required to infer loss of strength across the whole spectrum, and this assessment must be stable over time, regardless of changes in sports performance- this will mean that classification can achieve its purpose and that for a given level of impairment, athletes can train to improve their performance and be as successful in Paralympic Sport as possible.

Conclusions:

- Assessment of muscle strength in Paralympic Sport should be conducted with the aim of inferring loss of muscle strength as a result of a condition.
- Isometric, multi-joint measures that include key muscle groups should be developed to provide a valid method of inferring loss of muscle strength in Para-athletes

- Future research will be required to evaluate the training resistance of methods that are developed and to validate the concepts that were drawn from the non-disabled literature.

Acknowledgments

No sources of funding were used to assist in the preparation of this review. The authors have no potential conflicts of interest that are directly relevant to the content of this review.

References

1. Tweedy SM, Vanlandewijck, Y.C. International Paralympic Committee Position Stand - Background and Scientific Rationale for Classification in Paralympic Sport. *Br. J. Sports Med.* 2011;45(4):259-269.
2. International Paralympic Committee. *IPC Classification Code and International Standards.* Bonn: International Paralympic Committee; 2015.
3. World Health Organisation. *International Classification of Functioning, Disability and Health (ICF).* Geneva: World Health Organisation; 2001.
4. Tweedy SM. Taxonomic theory and the ICF: foundations for a unified disability athletics classification. *Adapted Physical Activity Quarterly.* 2002;19:220-237.
5. Connick MJ, Beckman, E.M., Ibusuki, T., Malone, L., Tweedy, S.M. Evaluation of methods for calculating maximal allowable standing height in amputees competing in Paralympic athletics. *Scandinavian Journal of Science and Medicine in Sport.* 2015;Epub ahead of print.
6. Tweedy SM, Beckman, E.M., Connick, M.J. Paralympic Classification - conceptual basis, current methods and research update *PM&R.* 2014;6(8):s11-s17.
7. Spungen AM, Wang, J., Pierson, R.N., Bauman, W.A. Soft tissue body composition differences in monozygotic twins discordant for spinal cord injury. *J. Appl. Physiol.* 2000;88(4):1310-1315.
8. Dalgas U, Stenager, E., Jakobsen, J., Petersen, T., Hansen, H., Knudesen, C., Overgaard, K., Ingemann-Hansen, T. Fatigue, mood and quality of life improve in MS patients after progressive resistance training *Mult. Scler.* 2010;16:480-490.
9. Duran FS, Lugo, L., Ramirez, L., Eusse, E. Effects of an exercise program on the rehabilitation of patients with a spinal cord injury. *Arch. Phys. Med. Rehabil.* 2001;82(10):1349-1354.
10. Hicks A, Martin, KA, Ditor, DS, Latimer, AE, Craven, C, Bugaresti, J, McCartney, N. Long-term exercise training in persons with spinal cord injury: effects on strength, arm ergometry performance and psychological well-being. *Spinal Cord.* 2003;41:34-43.
11. Spector S, Gordon, PL, Feuerstein, IM, Sivakumar, K, Hurley, BF, Dalakas, MC. Strength gains without muscle injury after strength training in patients with postpolio muscular atrophy. *Muscle Nerve.* 1996;19:1282-1290.
12. Nash MS, van de Ven, I., van Elk, N., Johnson, B.M. Effects of circuit resistance training on fitness attributes and upper-extremity pain in middle-aged men with paraplegia. *Arch. Phys. Med. Rehabil.* 2007;88(1):70-75.
13. Fimland MS, Helgerud, J., Gruber, M., Leivseth, G., Hoff, J. Enhanced neural drive after maximal strength training in multiple sclerosis patients. *European Journal of Applied Physiology.* 2010;110:435-443.
14. Scholtes VAB, Becher, J.G., Comuth, A., Dekkers, H., Van Dijk, L., Dallmeijer, A.J. Effectiveness of functional progressive resistance exercise strength trainin on musle strength and mobility in children with cerebral palsy: a randomized controlled trial *Dev. Med. Child Neurol.* 2010;published online 28th January 2010.
15. Damiano D, Abel, MF. Functional outcomes of strength training in spastic cerebral palsy. *Arch. Phys. Med. Rehabil.* 1998;79:119-125.

16. Dodd K, Taylor, NF., Damiano, DL. A systematic review of the effectiveness of strength training programs for people with cerebral palsy. *Arch. Phys. Med. Rehabil.* 2002;83:1157-1164.
17. Damiano D, Abel, MF. Functional outcomes of strength training in spastic cerebral palsy. *Archives of physical medicine and rehabilitation.* 1998;79:119-125.
18. Dodd K, Taylor, NF., Damiano, DL. A systematic review of the effectiveness of strength training programs for people with cerebral palsy. *Archives of physical medicine and rehabilitation.* 2002;83:1157-1164.
19. Chiu H, Ada, L., Butler, J., Coulson, S. Relative contribution of motor impairments to limitations in activity and restrictions in participation in adults with hemiplegic cerebral palsy. *Clin. Rehabil.* 2010;24:454-462.
20. Tweedy S. Biomechanical consequences of impairment: a taxinomically valid basis for classification in a unified disabliity athletics system. *Research quarterly for exercise and sport.* 2003;74(1):9-16.
21. Ng SSM, Shepherd, R.B. Weakness in patients with stroke: implications for strength training in neurorehabilitation. *Physical Therapy Reviews.* 20000;5:227-238.
22. Sharp SA, Brouwer, B.J. Isokinetic strength training of the hemiparetic knee: effects on function and spasticity. *Archives of physical medicine and rehabilitation.* 1997;78:1231-1236.
23. Ada L, Dorsch, S., Canning, C. Strengthening interventions increase strength and improve activity after stroke: a systematic review. *Aust. J. Physiother.* 2006;52(4):241-248.
24. Abernethy P, Wilson, G, Logan, P. Strength and power assessment. Issues, controversies and challenges. *Sports Med.* 1995;19(6):401-417.
25. Daniels L, Worthingham, C. *Muscle Testing Technique of Manual Examination.* 5th ed. Philadelphia: WB Saunders Co; 1986.
26. International Paralympic Committee. *IPC Athletics Classification Rules and Regulations* Bonn, Germany: Author; 2013.
27. Bohannon R. Manual muscle testing does it meet the standards of an adequate screening test? *Clin. Rehabil.* 2005;19:662-667.
28. Tweedy SM, Williams, G., Bourke, J. Selecting and modifying methods of manual muscle testing for classification in Paralympic sport. *European Journal of Adapted Physical Activity.* 2010;3(2):7-16.
29. International Paralympic Committee. *IPC Classification Code September 2007.* Bonn: International Paralympic Committee; 2007.
30. Cormie P, McGuigan, M.R., Newton, R.U. Developing maximal neuromuscular power. Part 1 - Biological basis of maximal power production. *Sports Med.* 2011;41(1):17-38.
31. Bigland-Ritchie B. EMG/Force relations and fatigue of human voluntary contractions. *Exerc. Sport Sci. Rev.* 1981;9(1):75-118.
32. Hof AL. EMG and muscle force: an introduction. *Human Movement Science.* 1984;3:119-153.
33. Reeves ND, Narici, M.V., Maganaris, C.N. In vivo human muscle structure and function: adaptations to resistance training in old age. *Exp. Physiol.* 2004;89:675-689.
34. Mahler P, Mora, C., Gremion, G. Isotonic muscle evaluation and sprint performance. *Excel.* 1992;8:139-145.
35. Murphy A, Wilson, GJ., Pryor JF. The use of isoinertial force mass relationship in the prediction of dynamic human performance. *Eur. J. Appl. Physiol.* 1994;69:250-257.

36. Dowson M, Nevill, ME., Lakomy, HK., Hazeldine, RJ. Modelling the relationship between isokinetic muscle strength and sprint running performance. *J. Sports Sci.* 1998;16:257-265.
37. Cronin J, Hansen, KT. Strength and power predictors of sports speed. *J. Strength Cond. Res.* 2005;19(2):349-357.
38. Berg K, Miller, M., Stephens, L. Determinants of 30 meter sprint time in pubescent males. *J. Sports Med.* 1986;26:225-231.
39. Bloomfield J, Blanksby, BA., Ackland TR. The influence of strength training on overhead throwing velocity of elite water polo players. *Aust. J. Sci. Med. Sport.* 1990;22:63-67.
40. Considine W, Sullivan, W. Relationship of selected tests of leg strength and leg power on college men. *Rearch Quarterly for Exercise and Sport.* 1973;44:404-415.
41. Kukolj M, Ropret, R, Ugarkovic, D, Jaric, S. Anthropometric, strength and power predictors of sprinting performance. *J. Sports Med. Phys. Fitness.* 1999;39(2):120-122.
42. Kollock R, Van Lunen, B.L., Ringleb, S.I., Onate, J.A. Measures of functional performance and their association with hip and thigh strength. *J. Athl. Train.* 2015;50(1):14-22.
43. Thorstensson A, Hulten, B., von Doblen, W., Karlsson, J. Effect of strength training on enzyme activities and fibre characteristics in human skeletal muscle. *Acta Physiol. Scand.* 1976;96:392-398.
44. Baker D, Wilson, G, Carlyon, B. Generality versus specificity: a comparison of dynamic and isometric measures of strength and speed-strength. *European Journal of Applied Physiology.* 1994;68:350-355.
45. Sale D, Martin, JE, Moroz, DE. Hypertrophy without increased isometric strength after weight training. *European Journal of Applied Physiology.* 1992;64:51-55.
46. Keogh JWL. Paralympic Sport: an emerging area for research and consultancy in sports biomechanics. *Sports Biomech.* 2011;10(3):234-253.
47. Wilson G, Murphy, AJ. The use of isometric tests of muscular function in athletic assessment. *Sports Med.* 1996;22(1):19-37.
48. Strass D. Force-time and electromyographical characteristics of arm shoulder muscles in explosive type force production in sprint swimmers. *J Swim Res.* 1991;7:19-27.
49. Secher N. Isometric rowing strength of experienced and inexperienced oarsmen. *Med. Sci. Sports Exerc.* 1975;7:280-283.
50. Murphy A, Wilson, GJ, Pryor, JF, Newton, RU. Isometric assessment of muscular function: The effect of joint angle. *J. Appl. Biomech.* 1995;11:205-215.
51. Van den Tillaar R, Saeterbakken, A.H., Ettema, G. Is the occurance of the sticking region the result of diminishing potentiation in the bench press? *J. Sports Sci.* 2012;30(6):591-599.
52. Marcora S, Miller, M.K. The effect of knee angle on the external validity of isometric measures of lower body neuromuscular function. *J. Sports Sci.* 2000;18:313-319.
53. Bemben MG, Clasey, J.L., Massey, B.H. The effect of the rate of muscle contraction on the force-time curve parameters of male and female subjects. *Res. Q. Exerc. Sport.* 1990;61:96-99.
54. Christ CB, Boileau R.A., Slaughter M.H., Stillman R.J., Cameron J. The effect of test protocol instructions on the measurement of muscle function in adult women. *J. Orthop. Sports Phys. Ther.* 1993;18(3):502-510.
55. Viitasalo J, Aura, O. Seasonal fluctuation of force production in high jumpers. *Can. J. Appl. Sport Sci.* 1984;9:209-213.

56. Viitasalo J, Hakkinen, K, Komi, PV. Isometric and dynamic force production and mucle fibre compostion in man. *Journal of Human Movement Studies.* 1981;7:199-209.
57. West DJ, Owen, N.J., Jones, M.R., Bracken, R.M., Cook, C.J., Cunningham, D.J., Shearer, D.A., Finn, C.V., Newton, R.U., Crewther, B.T., Kilduff, L.P. Relationships between force-time characteristis of the isometric midthigh pull and dynamic performance in professional rugby league players. *J. Strength Cond. Res.* 2011;25(11):3070-3075.
58. McNair P, Depledge, J., Brettkelly, M., Stanley, SN. Verbal encouragement: effects on maximum effort voluntary muscle action. *Br. J. Sports Med.* 1996;30:243-245.
59. Beckman EM, Newcombe, P., Vanlandewijck, Y., Connick, M.J., Tweedy, S.M. A novel strength test battery to permit evidence-based Paralympic classification. *Medicine.* 2014;94(4):1-8.
60. Turbanski S, Schmidtbleicher, D. Effects of heavy resistance training on strength and power in upper extremities in wheelchair athletes. *J. Strength Cond. Res.* 2010;24(1):8-16.

Table 1. Definitions for ICF terms that are used in a classification context

ICF term	Definition
Health condition	Diseases, disorders and injuries and are classified in the *International Classification of Diseases, 10th Revision*, not in the *ICF*. Cerebral palsy, spina bifida and multiple sclerosis are examples of health conditions
Body structures	Anatomical parts of the body such as organs and limbs and their components. The body structures of central concern in Paralympic sport are those related to movement and include the motor centres of the brain and spinal cord, as well as the upper and lower limbs
Body functions	Physiological functions of body systems (eg; cardiovascular functions and sensory functions). The body functions of central concern in Paralympic sport are neuromusculoskeletal function, visual function and intellectual function
Impairments	Problems body function and structure such as significant deviation or loss. A person with a contracture at the right elbow would be described as having *impaired* range of movement.
Activity	The execution of a task or action by an individual. The term *activity* encompasses all sports-specific movement, including running, jumping, throwing, wheelchair pushing, shooting and kicking
Activity Limitation	Difficulty a person may have in executing an activity. In Paralympic sport activity, limitations refer to difficulty executing the sports-specific movements required for a particular sport. Running is a core activity in the sport of athletics and a person

	who has difficulty running is said to have an *activity limitation* in running.

Figure 1. Example of a test of strength that incorporates key muscle groups for running in a standardised position (hip angle of 60 degrees and knee angle of 120 degrees) where force is applied slowly to the force transducer in an isometric fashion to obtain maximal voluntary strength.