A BATTERY OF STRENGTH TESTS FOR EVIDENCE-BASED CLASSIFICATION IN PARA SWIMMING

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ABSTRACT

This study examined the validity of isometric strength tests for evidence-based classification in Para swimming. Thirty non-disabled participants and forty-two Para swimmers with physical impairment completed an isometric strength test battery designed to explain activity limitation in the freestyle discipline. Measures pertaining to dominant and non-dominant limb strength and symmetry were derived from four strength tests that were found to be reliable in a cohort of non-disabled participants (ICC = 0.85-0.97; CV = 6.4-9.1%). Para swimmers had lower scores in strength tests compared with non-disabled participants (d = 0.14-1.00) and the strength test battery successfully classified 95% of Para swimmers with physical impairment using random forest algorithm. Most of the strength measures had low to moderate correlations (r = 0.32 to 0.53; p≤0.05) with maximal freestyle swim speed in the cohort of para swimmers. Although, fewer correlations were found for both groups when Para swimmers with hypertonia or impaired muscle power were analysed independently, highlighting the impairment-specific nature of activity limitation in Para swimming. Collectively, the strength test battery has utility in Para swimming classification to infer loss of strength in Para swimmers, guide minimum eligibility criteria, and to define the impact that strength impairment has on Para swimming performance.

INTRODUCTION

Classification plays an integral role in Paralympic sport and aims to promote increased participation in sport by people with disabilities by minimising the impact that impairment has on the competition outcome. Para swimming, one of the most popular Paralympic sports, uses a functional classification system to group athletes with an eligible physical impairment. Unfortunately, studies have shown current classification methods fail to delineate performance between some classes and disadvantage athletes with certain types of physical impairment within classes (Burkett et al., 2018; Daly & Vanlandewijck, 1999; Wu & Williams, 1999). The shortcomings of the current classification system may result, at least in part, from issues with measurement weighting and aggregation stemming from a lack of understanding of the relationship between impairment and swimming performance (Tweedy, Beckman, & Connick, 2014). World Para swimming have mandated that research be conducted to provide the scientific evidence to underpin a new classification system in Para swimming (International Paralympic Committee, 2015).

A key step towards evidence-based classification systems in Para sport is developing valid tests of impairment and establishing their relationship with sports performance. It is important to note that these tests do not directly measure impairment, but infer impairment based on knowledge of intact, unimpaired body structures and functions (Tweedy, Mann, & Vanlandewijck, 2016). Their purpose is to describe Para athletes' type, location and severity of impairment to estimate their subsequent activity limitation for a given sporting event. The International Paralympic Committee (IPC) Position Stand stipulates that valid impairment tests will have several measurement properties (Tweedy & Vanlandewijck, 2011). These include impairment tests being precise and reliable, ratio-scaled, specific to the impairment of interest, quantitative, account for a significant portion of variance in performance, and as training resistant as possible.

Muscular strength and power are key determinants of success in competitive swimming and their importance to propulsion during swimming is widely accepted (Crowley, Harrison & Lyons, 2017; Loturco et al., 2016). Para swimmers with health conditions such as spinal cord injury, cerebral palsy and Charcot-Marie-Tooth disease have impairments to the central and peripheral nervous systems, musculoskeletal system or links between these structures, that result in loss of muscular strength and power and affect their swimming performance (Dingley, Pyne, & Burkett, 2014; Dingley, Pyne, Youngson & Burkett, 2015; Morouco et al., 2011). Classifying strength impairment of Para swimmers with motor-complete spinal cord injury is relatively straightforward as these athletes have a non-progressive loss of voluntary motor control that corresponds to the level of lesion (Connick et al., 2018). Other progressive and non-progressive medical conditions such as cerebral palsy, motor-incomplete spinal cord injury, polio, and Charcot-Marie-Tooth disease have inconsistent clinical manifestations. Para swimmers with these conditions have loss of voluntary motor control that varies considerably for the severity of impairment and its presentation in the trunk, and upper and lower limb extremities.

Manual Muscle Testing (MMT) techniques are currently used to assess the severity and location of impairment by subjectively inferring swimmers' loss of strength by rating whether they can produce what is termed 'normal' resistance around joints (International Paralympic Committee, 2017). Although having several advantages, including being easy to administer, widely utilised in clinical practice and inexpensive, MMT techniques lack key measurement properties required for evidence-based classification. Inter- and intra-tester reliability is poor due to the subjective assessment of muscle strength and the ordinal measures derived from MMT are limited in defining their relationship with sporting performance (Beckman, Connick, & Tweedy, 2017; Bohannon, 2005).

Guidelines have recently been published for the development of instrumented tests of muscle strength for the purposes of classification (Beckman, Connick & Tweedy, 2017). The key recommendations were to develop isometric measures of muscle strength that assess Para athletes' force generating capacity in multi-joint positions that are standardised and specific to the sport of interest. Such tests will provide the most valid measures for inferring loss of muscle strength for classification as they determine the maximal force generating capacity of a muscle or muscle group (Cormie, McGuigan, & Newton, 2011), are more likely to be resistant to training than dynamic muscular strength and power tests that typically have greater specificity to athletic performance (Beckman et al., 2017; Loturco et al., 2016), and might have strong and meaningful associations with sports performance in Para athletes with strength impairment (Beckman, Conncik & Tweedy, 2016; Hyde et al., 2017).

As isometric strength tests are limited in assessing muscular strength through full range of motion, important steps in developing tests for classification include identifying the principal muscle groups and actions that are involved in the sport (Beckman et al., 2017; Burkett et al., 2017). Most studies in able-bodied swimmers have investigated front crawl swimming and have reported the latissimus dorsi, pectoralis major, and teres minor play important roles in stabilising and mobilising the shoulder into extension and adduction during the early and late underwater pull phases that are primarily responsible for propulsion (Amaro, Morouco, Marques, Fernandes & Marinho, 2017; Martens, Figueiredo & Daly, 2015). Agonist antagonist activity of muscles of the elbow joint (i.e. biceps brachii and triceps brachii) and wrist joint (i.e. brachioradialis, flexor carpi ulnaris, and extensor carpi ulnaris) stabilise the forearm and hand to overcome water drag during these propulsive actions (Martens et al., 2015).

Although the lower limb extremity contributes less to propulsion and swim velocity in front crawl than the upper limb extremity (Amaro et al., 2017; Bartolomeu, Costa & Barbosa, 2018), the quadriceps and hamstring muscle groups mobilise the hip and knee joints to generate drag and lift forces in coordination with the arm stroke (Bartolomeu et al., 2018; Martens et al., 2015; Morouco, Marinho, Izquierdo, Neiva & Marques, 2015). Strength impairments in the lower limb extremity might have increased importance in the lower sport classes where drag is more important in discriminating between performances (Oh, Burkett, Osborough, Formosa & Payton, 2013), due to the role that the leg kick plays in stabilising the body and generating lift forces that allow swimmers to maintain streamlined body positions (Amaro et al., 2017; Bartolomeu et al., 2018; Psycharakis & Sanders, 2010). Lower body muscular strength and power are also key determinants of starts and turns performance with the gluteus maximus and triceps surae contributing to joint torque during hip extension and plantar flexion, respectively, to generate propulsive actions during certain components of a swim race (Jones, Pyne, Haff & Newton, 2018; Morouco, Marinho, Amaro, Perez-Turpin & Marques, 2012).

This study presents isometric strength tests that have been designed to infer loss of muscular strength in the upper and lower limb extremities for evidence-based Para swimming classification. The aims were to: (i) examine the predictive validity of isometric strength tests to discriminate between non-disabled participants and Para swimmers with physical impairments, (ii) establish the strength of association between isometric strength tests and freestyle swim performance in Para swimmers with strength impairments, and (iii) establish the test-retest reliability of isometric strength tests in non-disabled participants. Isometric strength tests might have utility in Para swimming classification if they discriminate Para swimmers with strength impairment from non-disabled participants, have meaningful associations with swimming performance in Para swimmers, and are found to be reliable.

METHODS

Participants

Data were collected from 72 participants including Para swimmers and non-disabled participants (Table 1). Para swimmers had an eligible physical impairment resulting in loss of muscle power. They had received national or international classification, were undertaking planned training regimes and competing at a national or international level. Non-disabled participants were recruited from University of the Sunshine Coast, Australia or Manchester Metropolitan University, United Kingdom. They were between the ages of 18 and 35 years of age, apparently healthy and recreationally active (undertaking planned exercise, training or sport at least twice a week for a minimum total of 80 minutes). These eligibility criteria were established to recruit a convenient sample of non-disabled participants with a wide range of activity backgrounds. Such a cohort was considered advantageous when examining the predictive validity of strength tests to identify participants with and without physical impairment. All participants gave their written informed consent to participate in this study under approved ethical guidelines (A/16/892).

Design

Isometric strength tests were developed by the research team consisting of experts in evidence-based classification and Para swimming sport science. Tests were designed to explain activity limitation in the freestyle discipline. They went through a development process that included consultation with a panel of coaches, Para swimmers, classifiers, administrators and sport science and medicine personnel, and were piloted in individuals with disabilities. Para swimmers completed the test battery during organised data collection events within Europe and Australia. They completed physical impairment and swimming-specific assessments around their training schedules during these events. Non-disabled participants and Para swimmers attended at least one 90-minute session where they undertook the finalised test battery comprising four strength tests. Para swimmers also attended a separate 30-minute session where their maximal freestyle swim performance was assessed. Non-disabled participants were asked to maintain their usual exercise or training regimes throughout their involvement in the study. Fifteen non-disabled participants repeated the test battery within a week to examine the test-retest reliability of strength tests.

Experimental procedures

Participants completed a questionnaire regarding demographics, their typical training regime (type and frequency of training), and training activity on the day of testing. Para swimmers also provided information pertaining to their training experience, competition standard attained, current sport class, and type of physical impairment. These data were verified against information attained from classification records listed in the IPC Sports Data Management System (https://db.ipc-services.org/sdms). Participants' stature and body mass were recorded prior to the strength tests. Stature was estimated from sitting height recorded from a custom-built chair for Para swimmers with no or poor locomotor ability. Ratios of sitting height to standing height available in the World Para swimming Classification Manual were used for estimations (International Paralympic Committee, 2017).

The order of the strength tests was randomised. All participants undertook the test battery under the instruction and supervision of the principal researcher. Isometric strength was assessed using an S-type strain gauge attached to a custom-made aluminium frame that provided force-time data collected at 200 Hz (Ergotest, Porsgrunn, Norway). The strength test battery consisted of 4 tests that yielded 8 outcome measures: dominant and non-dominant (i) shoulder extension strength, (ii) shoulder flexion strength, (iii) hip extension strength and (iv) hip flexion strength. The strength test protocols are outlined in detail in Supplementary Table 1. Following practice trials, participants performed 3 maximal effort trials for each test. Once in position, participants were instructed to slowly build up their applied force until reaching their maximal effort within 2-3 seconds. All contractions lasted between 4 and 10 seconds and were performed on each minute, giving participants at least 50 seconds rest between consecutive trials (Beckman, Newcombe, Vanlandewijck, Connick, & Tweedy, 2014). Each participant was given the same set of instructions before and during contractions. The best trial indicated by the highest maximal voluntary contraction (MVC) was used for analysis. For each strength test a symmetry index was calculated as a ratio of their non-dominant to dominant limb strength.

Para swimmers maximal clean swim speed was assessed over a 10 m calibrated test zone for their preferred freestyle swim stroke. Clean swim speed was determined using standard two-dimensional video analysis procedures. Output from a 50 Hz video camera (Sony HDR HC9, Sony Corporation, Japan) placed perpendicular to the swimmers' direction of travel was captured using commercial software (Dartfish TeamPro version 7.0, Dartfish UK). Participants were instructed to reach maximal swim speed prior to the start of the 10 m test zone and sustain maximal swim speed until 5 m past the end of the test zone. They performed two maximal effort trials separated by a minimum of 3 minutes' rest and the fastest time to cover the 10 m test zone was used to compute their maximal clean swim speed. The recorded maximal clean swim speeds were found to have strong relationships with personal best race times for 50 m freestyle (R^2 = 0.914) and 100 m freestyle (R^2 = 0.892) in our participant cohort. Maximal clean swim speed was not assessed for three Para swimmers with hypertonia due to limited time with these participants.

Statistical analyses

Statistics were calculated using R version 3.4.0 (R Core Team, 2017). Shapiro-Wilks tests indicated non-uniform distribution of several test measures for Para swimmers with hypertonia or impaired muscle power. A Kruskal-Wallis rank test was used to determine significant effects between hypertonia, impaired muscle power and non-disabled participant groups. Wilcoxon tests were used post hoc to determine the source of significant effects, with p-values adjusted for multiple comparisons using the Benjamini and Hochberg method. Cliff's Delta (d), a non-parametric measure of effect size, was calculated with 95% confidence intervals to indicate the magnitude of difference in strength test measures between Para swimmers and non-disabled participants (Rogmann, 2013). Sex-specific differences were calculated as there were significant differences found in isometric strength measures between non-disabled male and female participants.

Random forest algorithm was used to establish the predictive validity of strength tests to classify participants with and without strength impairment. Random forest is a non-linear machine learning technique that uses an ensemble learning method for classification and regression (Liaw & Wiener, 2002; Woods, Veale, Fransen, Robertson & Collier, 2018). Separate models were built to determine the prediction accuracies based on sex. The importance of predictor variables was determined using the mean decrease in accuracy, which indicates the decrease in prediction accuracy that occurs when a single variable is excluded during the out-of-bag error calculation (Liaw & Wiener, 2002; Woods et al., 2018).

Spearman correlation coefficients were calculated to assess the strength of association between the Para swimmers' strength test measures and maximal clean swim speeds. Correlations were calculated for the entire cohort of Para swimmers and independently for the hypertonia and impaired muscle power groups. Significance was set at an alpha value of ≤ 0.05. The strength of correlations was interpreted as negligible (0.0-0.2), low (0.21-0.40), moderate (0.41-0.60), high (0.61-0.80) and very high (>0.81) (Mukaka, 2012).

For non-disabled participants, normality of distribution was confirmed using the Shapiro-Wilk test. Unpaired sample t-tests assuming equal variances were used to determine differences between male and female participant groups. Reliability assessments were calculated using Hopkins' reliability spreadsheet (Hopkins, 2015). Paired sample t-tests were conducted to identify any systematic change in test measures between repeated trials. Intra-class correlation coefficients (ICC) method 3,1, standard error of measurement (SEM) scores expressed in the original units of measurement, and coefficient of variation (CV) scores were calculated to provide an absolute assessment of reliability (Hopkins, 2000).

RESULTS

Differences in strength scores between Para swimmers and non-disabled participants are shown in Figure 1. Para swimmers showed significantly lower strength scores for all tests, except for shoulder flexion strength in female Para swimmers (Figure 1C and 1D) and dominant hip flexion strength in male Para swimmers with hypertonia (Figure 1G). Para swimmers showed larger differences in strength scores compared with non-disabled participants for their non-dominant limbs (Figure 1). This was illustrated in differences between non-disabled participants and Para swimmers for symmetry indexes calculated for shoulder extension strength (mean ± range = 0.96 ± 0.12 versus 0.82 ± 0.51; d = 0.81, p<0.01), shoulder flexion strength (mean ± range = 0.94 ± 0.14 versus 0.84 ± 0 .55; d = 0.52, p<0.01), hip extension strength (mean ± range = 0.94 ± 0.16 versus 0.48 ± 0.99; d = 0.77, p<0.01), and hip flexion strength (mean ± range = 0.95 ± 0.11 versus 0.49 ± 0.97; d = 0.89, p<0.01).

Random forest that included all strength test measures as predictor variables successfully classified 25/26 (96 %) male Para swimmers and 15/16 (94 %) female Para swimmers. The mean decrease in accuracy scores were similar for the male and female participant groups, with lower limb strength and symmetry measures typically being the most important variables for prediction of participants with and without physical impairment (Figure 2).

Maximal clean swim speeds were 1.14±0.34 m.s^{-1} (range 0.21 to 1.62 m.s^{-1}) for male Para swimmers and 1.03±0.29 m.s^{-1} (range 0.55 to 1.51 m.s^{-1}) for female Para swimmers. Para swimmers with hypertonia (1.19±0.27 $m.s^{-1}$; range 0.55 to 1.62 $m.s^{-1}$) had slightly faster clean swim speeds than Para swimmers with Impaired muscle power (1.00±0.35 $m.s^{-1}$; range 0.21 to 1.51 $m.s^{-1}$), although there was no significant difference found between groups (p = 0.12). All strength scores had significant low to moderate correlations (r=0.32 to 0.53, p≤0.05) with maximal clean swim speed in the combined cohort of Para swimmers, except for non-dominant shoulder flexion (r=0.15, p=0.35) (Figure 3).

There were fewer strength scores that had significant correlations with clean swim speeds when hypertonia or impaired muscle power groups were analysed independently (Figure 3). Dominant and non-dominant shoulder extension strength had the strongest correlations with maximal clean swim speed for Para swimmers with hypertonia (r=0.46 to 0.66, p≤0.04) and impaired muscle power (r=0.47 to 0.51, p≤0.04). Para swimmers with hypertonia also showed significant correlations between clean swim speed and strength scores for dominant shoulder flexion (r=0.66, p<0.01) and dominant hip flexion (r=0.44, p=0.05), while there were no correlations found for other strength tests (r=0.27 to 0.38, p=0.10 to 0.25). Para swimmers with impaired muscle power reported no significant correlations between clean swim speed and strength scores for shoulder flexion (r=-0.12 to 0.12, p =0.61 to 0.63), hip extension (r=0.12 to 0.31, p=0.20 to 0.30), or hip flexion (r=0.12 to 0.19, p=0.45 to 0.61).

Reliability assessments indicated all strength tests to be reliable in non-disabled participants (Table 2). There were no significant changes in outcome measures between repeated trials, with participants' absolute and relative changes ranging from -7 ± 4 N to 2 ± 18 N and -5 ± 10 % to 3 ± 12 %, respectively. Strength test measures in non-disabled participants are shown in Figure 1 and Supplementary Table 2. Unpaired sample t-tests assuming equal variances indicated significant differences (p<0.01) between non-disabled male and female participants for all strength tests, except for measures of strength symmetry.

DISCUSSION

This study aimed to establish the validity and reliability of isometric strength tests for classification of Para swimmers with physical impairment. A key measurement property of these tests is their ability to identify Para swimmers with an eligible strength impairment. Eligibility is determined by type of physical impairment, as well as impairment severity that must conform to the minimum eligibility criteria. The isometric strength tests presented in this study were found to differ between Para swimmers with physical impairments and non-disabled participants (Figure 1), suggesting they will be useful in inferring loss of strength and guiding minimum eligibility criteria in Para swimming cohorts.

The strength test measures reported for non-disabled participants provide a useful benchmark to infer loss of muscle strength in Para swimmers, although there are several points to consider beforehand. First, there were significant differences in strength scores between non-disabled male and female participants suggesting that sex-specific benchmarks should be used to infer loss of strength in Para swimmers with physical impairment (Supplementary Table 2). Second, the non-disabled participants showed considerable variations in strength scores (Figure 1), likely due to the range in reported activity backgrounds (Table 1). Given that muscular strength is responsive to training type, volume and intensity (Crowley et al., 2017) it is important that normative values are collected in a larger sample of able-bodied swimmers with various training ages and regimes. This will provide classifiers with normative values in non-disabled participants stratified by age, sex and training status so that they can accurately infer Para swimmers' strength impairments.

Supporting the predictive validity of the isometric strength test battery, the random forest algorithm had a 95 % success rate in correctly classifying participants with and without physical impairment based on strength test measures. There were two Para swimmers that were incorrectly classified as non-disabled participants. The first was a male Para swimmer with hemiplegic cerebral palsy that competes in the S6 class based on classification of motor coordination impairment, and so it is possible that that this participant is not affected by strength impairment. For Para swimmers with hypertonia, the current classification system assigns class based on the assessment of strength, motor coordination or range of movement depending on which one of these is judged to be most affected by the Para swimmer's health condition (International Paralympic Committee, 2017). It is interesting that all Para swimmers with hypertonia in this study compete in their current sport class based on assessment of motor coordination impairment. The high success rate of the random forest in classifying these Para swimmers using isometric strength and symmetry scores indicates that these Para swimmers have strength impairments that affect their swimming performance (Figure 3). This finding highlights the complexity of these Para swimmers' health conditions, and that classification should collectively account for impairments in strength, motor coordination and range of motion for these swimmers.

The incorrect classification of the female Para swimmer by the random forest algorithm raises several questions of the isometric strength test battery. This Para swimmer has an incomplete L4-L5 spinal cord injury and competes in the S8 sport class at Paralympic and World Championship standard. The random forest algorithm assigned 40 % of the votes to the priori case most likely as the participant's strength scores were within or higher than the lower and upper quartiles for scores in non-disabled females, except for dominant and non-dominant hip extension. This highlights the requirement of obtaining normative values in highly trained able-bodied swimmers to accurately infer strength impairment. Further, based on their classification records the Para swimmer was most affected by limited strength around the ankle joint. Active ankle range of motion is important to effectively orientate the foot segment during leg kicking to generate drag and lift forces (Connaboy et al., 2016), and plantar flexion at the ankle joint contributes to propulsion during starts and turns (Jones et al., 2018; Morouco et al., 2012). Although active range of motion assessments might explain part of this swimmer's activity limitation (Nicholson et al., 2018), these results indicate that the isometric strength test battery is not entirely comprehensive.

An important aspect of this study was examining the convergent validity of isometric strength tests by establishing their strength of association with freestyle swim performance. When the entire para swimming cohort was included in analyses there were low to moderate correlations found between maximal swim speed and all isometric strength scores, except for non-dominant shoulder flexion (Figure 3). Para swimmers showed the strongest correlations between isometric shoulder extension strength and maximal clean swim speed (Figure 3A and 3B). The upper limb extremity contributes to most of the propulsive force during tethered front crawl swimming (Amaro et al., 2017; Morouco et al., 2015), and the shoulder position during this test represented the start of the underwater push phase where able-bodied swimmers achieve the highest absolute hand speeds (Samson, Monnet, Bernard, Lacouture & David, 2015). The lower limb extremity contributes less to propulsion in front crawl swimming (Amaro et al., 2017; Morouco et al., 2015), which explains the lower correlations found between hip flexion and extension strength and freestyle swim performance in the combined cohort of Para swimmers (Figure 3). The leg kick is important in stabilising and controlling body roll in coordination with the arm stroke (Bartolomeu et al., 2018; Psycharakis & Sanders, 2010) and generates drag and lift forces that are likely to have higher contributions to instantaneous swim velocity in cases where the arm stroke is limited by impairment (Morouco et al., 2015; Bartolomeu et al., 2018). However, these tests might not comprehensively describe knee flexion and plantar flexion strength impairments that relate to starts and turns performance (Dingley et al., 2015; Jones et al., 2018) or propulsive forces during swim kicking (Connaboy et al., 2016).

Ensuring that the isometric strength test battery is comprehensive and parsimonious is important to consider before its implementation into a revised classification system. It is important to highlight that there were fewer correlations found between strength scores and maximal swim speeds when hypertonia and impaired muscle power groups were analysed independently (Figure 3). There are two explanations for these results. First, the wide range in location and distribution of strength impairment of Para swimmers that are within these groups affect the ability of any singular strength score to explain activity limitation in swimming. For instance, Para swimmers with impaired muscle power had a range of medical conditions (Table 1), some that might cause an even distribution of strength impairment across the upper and lower limbs (e.g. Charcot-Marie-Tooth disease) and others where strength impairment is confined to the trunk and lower limbs (e.g. complete SCI). Despite no correlation being found between lower limb strength and swim performance within this group (Figure 3), lower limb strength scores might be useful in explaining activity limitation in Para swimmers that have some remaining lower limb muscle power due to the role of leg kick in controlling body roll and stabilising the torso (Bartolomeu et al., 2018; Psycharakis & Sanders, 2010). Conversely, the assessment of trunk impairment might be more important in understanding activity limitation in Para swimmers with complete SCI that cannot leg kick due to having no lower limb muscle power (Altman et al., 2017; Altman et al., 2018; Psycharakis & Sanders, 2010).

Another explanation for the above, is that the type of physical impairment influences the association between strength tests and para swimming performance. It is interesting to note that Para swimmers with hypertonia showed a high correlation between dominant shoulder flexion and maximal clean swim speed ($r=0.66$, $p<0.01$), while there was no correlation found in Para swimmers with impaired muscle power (Figure 3C). This test was included in the battery as it was thought it would describe activity limitation in Para swimmers with severe impairments that use modified swim strokes (Prins & Murata, 2008). The positioning and action of the isometric shoulder flexion test is dissimilar to the kinematics of the underwater and recovery stroke phases of front crawl in able-bodied swimmers (Martens et al., 2015), which explains why no correlation was found with maximal swim speed in the impaired muscle power group. Conversely, the shoulder flexion strength test might be associated with the level of spasticity that affects Para swimmers with hypertonia and may be collinear with reduced motor coordination and range of motion that affects swim performance. Indeed, spasticity typically affects the flexor, adductor and internal rotator muscle groups more than their antagonists (Antunes, Rossato, Lima Kons, Luiz Sakugawa & Fischer, 2017; Delgado & Albright, 2003), and there is a high inverse association between the level of spasticity and voluntary motor function in people with health conditions such cerebral palsy and acquired brain injury (Delgado & Albright, 2003). These results highlight the impairment-specific nature of activity limitation in Para swimming, and that separate test batteries could be used to classify Para swimmers based on their aetiology of impairment.

The final aim of this study was to establish the test-retest reliability of strength tests. All tests were shown to be reliable in non-disabled participants, which is a prerequisite for evidence-based classification. Unfortunately, reliability in Para swimmers with hypertonia or impaired muscle power was not assessed due to limited time available to test these swimmers. Reliability data was collected in a convenient sample of non-disabled participants as measures that were found to be unreliable in this cohort would be unlikely to have acceptable reliability in Para swimmers with physical impairments (Beckman et al., 2014; Connick, Beckman, Deuble & Tweedy, 2016; Nicholson et al., 2018). Future studies should now establish the reliability of measures in Para swimmers with physical impairments to confirm their utility in Para swimming classification.

It is important to note that the application of this study's findings is limited without further research. This study intentionally limited tests that were designed to explain activity limitation in the freestyle discipline as there was limited time available to test Para swimmers. While there is likely to be some crossover between tests, other swim strokes are dependent on muscle groups and actions that were not assessed in this study (Martens et al., 2015). Targeted efforts are now required to develop strength tests that explain activity limitation in other swim strokes. Once this has been achieved, data collection in a larger sample of para swimmers can be conducted to define the relative impact that strength impairments have on swimming performance and guide valid classification structures (Altman et al., 2018; Connick et al., 2018; Hogarth, Payton, Van de Vliet, Connick & Burkett, 2018).

The isometric strength tests in this study also have several inherent limitations in classifying strength impairment. Namely, they are susceptible to athletes misrepresenting their abilities, they limit strength assessment to a fixed range of motion, strength scores might be susceptible to fatigue induced by prior activity or the tests themselves, and measures might be responsive to sport-specific training regimes (McGuigan, Newton, Winchester & Nelson, 2010). Even with these limitations, the objective measurement of strength impairment will undoubtedly improve the accuracy and transparency of Para swimming classification compared with current methods (Connick et al., 2018). Additionally, longitudinal assessments of isometric strength in Para swimmers will provide insights into their responsiveness to sport-specific training regimes so that classifiers can more accurately infer strength impairment, and machine learning algorithms can predict competitive performances from objective impairment measures to identify outlying performances caused by intentional misrepresentation of abilities (Hogarth et al., 2018).

CONCLUSIONS

This study presented isometric strength tests that were developed to permit evidence-based classification in Para swimming. Strength test measures had acceptable reliability in non-disabled participants - a requisite of evidence-based classification. Differences in strength test measures were found between non-disabled participants and Para swimmers with hypertonia or impaired muscle power, and random forest algorithm successfully classified 95% of Para swimmers. These results indicate that these tests will be useful in inferring loss of strength in Para swimmers with strength impairment and guiding minimum eligibility criteria. Dominant and non-dominant strength scores also had significant correlations with maximal freestyle swim speed in Para swimmers. This suggests that strength tests will be useful in explaining activity limitation in Para swimming, although results indicate that the type and aetiology of physical impairment influence the utility of some strength tests. Collectively, the results of this study make a significant contribution toward evidence-based methods of classification for Para swimmers with strength impairments.

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Figure captions

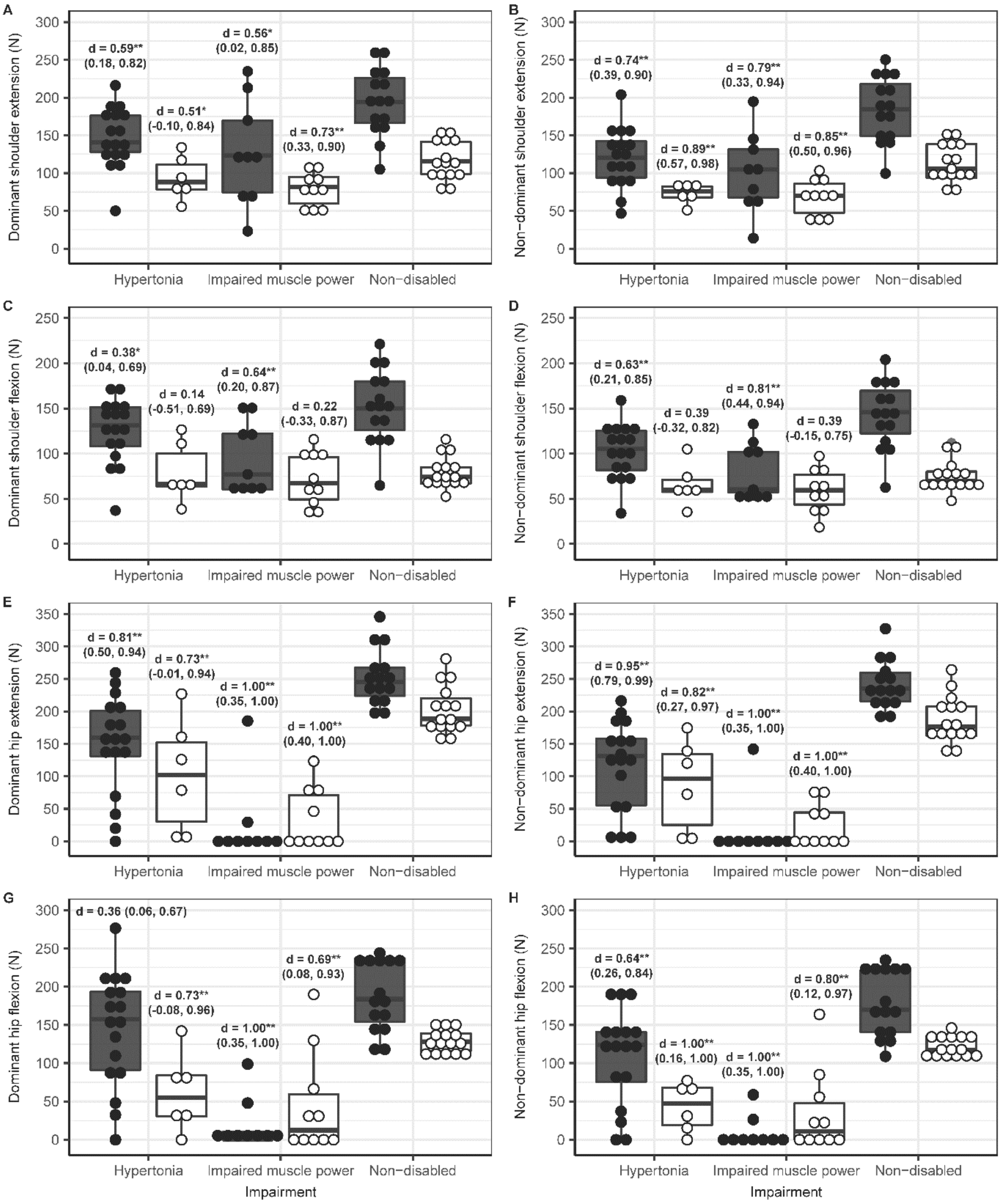


Figure 1. Strength test scores for Para swimmers with physical impairments and non-disabled participants. Scores a for (A) dominant and (B) non-dominant shoulder extension, (C) dominant and (D) non-dominant shoulder flexion, (E) dominant and (F) non-dominant hip extension, and (G) dominant and (H) non-dominant hip flexion. Data are reported for male (dark colour box plots) and female (white colour box plots) participants. Data are Cliff's delta scores with 95% CI indicating differences between para swimmers and non-disabled participants. *(p≤0.05) and **(p≤0.01) indicate significance.

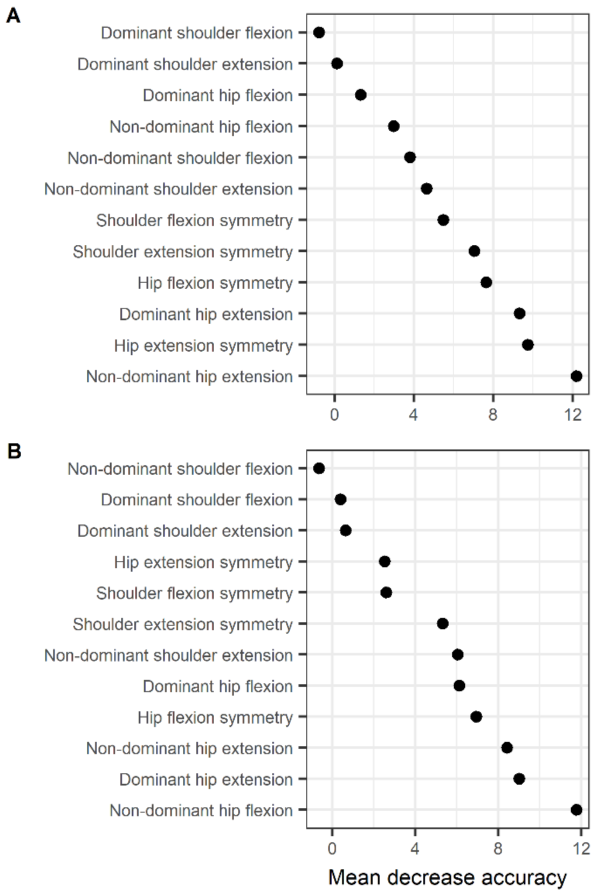


Figure 2. Mean decrease in accuracy scores indicating variable importance in classifying participants with and without physical impairment. Scores are reported for (A) male and (B) female participants. The variable importance score is the decrease in accuracy for each predictor variable when it is excluded from the classification model. The plot shows "non-dominant hip flexion" strength to be the strongest predictor in whether male and female participants did or did not have physical impairment.

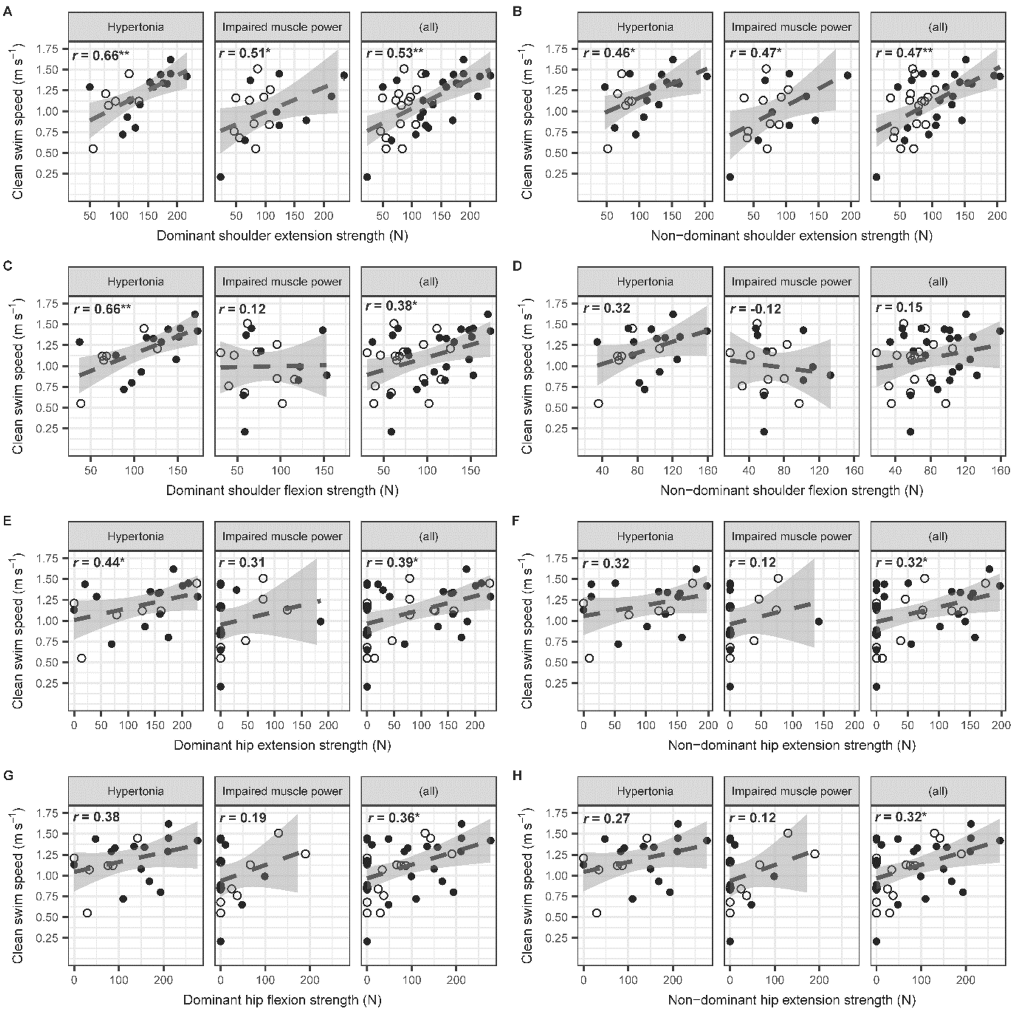


Figure 3. Strength of association between strength test scores and clean swim speed during maximal freestyle swimming. Data are Spearman correlation coefficients indicating strength of association between clean swim speed and (A) dominant and (B) non-dominant shoulder extension, (C) dominant and (D) don-dominant shoulder flexion, (E) dominant and (F) non-dominant hip extension, and (G) dominant and (H) non-dominant hip flexion. Plots show these associations for the combined cohort of para swimmers (n=39) and independently for Para swimmers with hypertonia (n=20) or impaired muscle power (n=19). Male (dark colour dots) and female (white colour dots) participants were pooled for analysis. *(p≤0.05) and **(p≤0.01) indicate significance.

Table 1. Characteristics of non-disabled participants and para swimmers with physical impairment.

		Hypertonia	Impaired muscle power	Non-disabled
	Males	n = 17	n = 9	n = 15
	Females	n = 6	n = 10	n = 15
Age (yrs)	Males	26.5 (7.0)	31.5 (7.7)	24 (4)
	Females	19.8 (4.1)	29.9 (10.2)	23 (5)
Body mass (kg)	Males	67.9 (9.8)	63.4 (14.4)	79.8 (11.4)
	Females	58.2 (10.30	56.2 (10.3)	68.1 (9.7)
Stature (cm)	Males	172.0 (8.8)	167.2 (12.4)	182.7 (7.7)
	Females	160.7 (9.0)	153.0 (13.4)	171.4 (7.0)
Reported exercise frequency (n/week)		Median = 7.5 Range = 2 to 15	Median = 7 Range = 3 to 14	Median = 6 Range = 3 to 14
Accumulated exercise duration (min/week)		Median = 720 Range = 180 to 1200	Median = 630 Range = 180 to 1170	Median = 360 Range = 150 to 1200
Reported activities		Competitive swimming (n=23) Resistance training (n=15)	Competitive swimming (n=19) Resistance training (n=6) Wheelchair rugby (n=1) Pilates and Yoga (n=1)	Resistance training (n=17) Recreational fitness[a] (n=13) Competitive sport[b] (n=12) Recreational sport[c] (n=8) Pilates and Yoga (n=4)
Competitive standard		International[d] (n=9) National (n=14)	International[d] (n=9) National (n=10)	
Competitive swim experience (yrs)		Median = 9.5 Range = 2 to 26	Median = 7 Range = 4 to 20	
S Class		S3 (n=1) S4 (n=4) S5 (n=2) S6 (n=5) S7 (n=2) S8 (n=7) S9 (n=2)	S1 (n=2) S3 (n=2) S4 (n=2) S5 (n=3) S6 (n=3) S7 (n=2) S8 (n=3) S9 (n=2)	
Medical conditions		Diplegic CP (n=8) Hemiplegic CP (n=9) Quadriplegic CP (n=4) Other (n=2)	Incomplete SCI (n=4) Complete SCI (n=8) Charcot-Marie-Tooth disease (n=2) Spina bifida (2) Polio (n=1) Other (n=3)	

CP = cerebral palsy, SCI = spinal cord injury. S Class = para swimmers' current class for freestyle, backstroke and butterfly swimming events. [a] Reported recreational fitness activities included moderate to high-intensity aerobic exercise, and group fitness classes. [b] Reported competitive sports training or competition included athletics, rugby, AFL, football, powerlifting and swimming. [c] Reported recreational sport competition included football, badminton, netball, jujitsu, dance and surfing. [d] Para swimmers were classified as international standard if they had competed during a Paralympic or World Championship event.

Table 2. Reliability of strength test measures in non-disabled participants.

		Trial 1 Mean (SD) (N)	Trial 2 Mean (SD) (N)	Δ T2 – T1 Mean (SD) (N)	SEM (N)	CV (%)	ICC (95% CI)
Shoulder extension strength	Dominant	170.3 (54.0)	172.0 (52.1)	1.7 (15.1)	10.2	6.9	0.97 (0.92-0.99)
	Non-dominant	156.0 (50.4)	157.8 (44.3)	1.9 (18.3)	12.9	8.5	0.94 (0.87-0.98)
Shoulder flexion strength	Dominant	128.1 (39.3)	122.3 (35.6)	-5.9 (12.1)	8.6	6.8	0.97 (0.91-0.99)
	Non-dominant	117.1 (37.0)	110.4 (33.4)	-6.7 (14.1)	10.0	7.7	0.96 (0.9-0.98)
Hip extension strength	Dominant	245.1 (46.9)	242.7 (46.1)	-2.5 (20.3)	14.4	6.4	0.91 (0.78-0.96)
	Non-dominant	225.3 (38.3)	222.7 (45.4)	-2.6 (24.5)	17.4	8.0	0.85 (0.65-0.94)
Hip flexion strength	Dominant	168.8 (46.7)	164.7 (42.7)	-4.2 (19.7)	14.0	9.1	0.91 (0.78-0.96)
	Non-dominant	157.2 (43.5)	155.5 (45.7)	-1.7 (15.2)	10.7	6.8	0.95 (0.89-0.98)

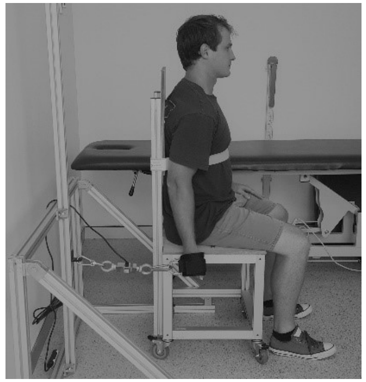
SEM = standard error of measurement, CV = coefficient of variation, ICC = intraclass correlation coefficient, CI = confidence interval.

Supplementary online material

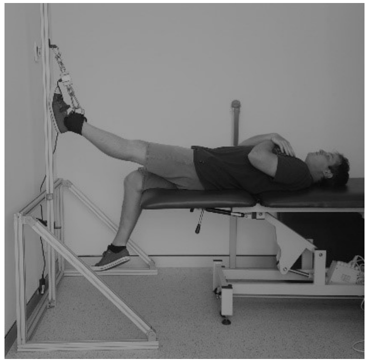
Supplementary Table 1. Description of isometric strength tests developed for Para swimming classification.

Test description	
Strength test: Shoulder extension **Procedure:** Participants sat with their trunk firmly supported by a back-rest and strapping. The cuff attached to the load cell was positioned at shoulder height in front of the arm being tested. The palm of the participants hand was placed downwards in the cuff with their elbow in a neutral position, and 90° of shoulder flexion. Positioning was confirmed using a digital inclinometer. The load cell was zeroed before trials with participants in the test position. Participants were instructed to apply maximum force to the load cell attachment while keeping their knuckles of the tested hand in contact with the upright of the strength rig. **Rationale:** The shoulder position in this test represents the mid-stroke position or the start of the underwater push phase. The upper limb extremity contributes to most of the propulsion during front crawl with the underwater push phase being an important due to the maximum hand speeds that are produced by able-bodied swimmers during this phase. This test also requires the participant to stabilise the elbow and wrist joint during muscular contractions, which is similar to joint actions during the underwater push and pull phases during front crawl. **Limitations in people with disabilities:** All para swimmers participating in this study could attain the shoulder position for this test. One para swimmer with spastic cerebral palsy could not perform a maximal effort without co-contraction of the elbow flexors, suggesting splinting or bracing methods might improve the validity and reliability of this test in people with disabilities.	

Supplementary Table 1 (continued). Description of isometric strength tests developed for Para swimming classification.

Test description	
Strength test: Shoulder flexion **Procedure:** Participants sat with their trunk firmly supported by a back-rest and strapping. The hand of the tested arm was placed in the cuff with the palm facing forward in a neutral position, elbow in a neutral position, and shoulder in a neutral. The load cell was attached to the strength rig at the height of the tested hand with the attachment taut when participants were in the test position. The load cell was zeroed before trials with participants shoulder in an extended position so that the load cell attachment was not taut. Participants were instructed to "take the slack" of the load cell attachment and pause prior to commencing the maximal effort test. **Rationale:** Although being dissimilar to front crawl kinematics in able-bodied swimmers, this test was included in the battery to explain activity limitation in para swimmers with severe physical impairments. Some of these para swimmers will use modified stroke patterns in the freestyle discipline, such as double armed backstroke. The shoulder positioning during this test might represent part of the underwater propulsion phase for these swimmers. **Limitations in people with disabilities:** While all para swimmers could attain the shoulder positioning for this test, one para swimmer with spastic cerebral palsy could not perform the shoulder action without co-contraction of the elbow flexors, suggesting splinting or bracing methods might improve the validity and reliability of this test in people with disabilities.	

Supplementary Table 1 (continued). Description of isometric strength tests developed for Para swimming classification.

Test description	
Strength test: Hip extension **Procedure:** Participants were in a supine position on a massage plinth with their legs off the bench at the popliteal crease. The tested leg was placed in an ankle cuff that attached the load cell to the strength rig so that the tested leg was in 15° of hip flexion, and neutral knee and ankle positioning. Arms were folded across the chest, and the foot of the tested leg was not in contact with the strength rig. Positioning was confirmed using a digital inclinometer that was placed on the mid-section of the thigh. The load cell was zeroed before trials with participants in the test position. **Rationale:** The leg kick contributes to propulsion and plays an important role in stabilising the body in coordination with the arm stroke during front crawl swimming. This test was designed to explain the contribution of the posterior chain in allowing para swimmers to maintain streamlined body positioning during freestyle. Hip extension strength is also important to starts and turns performance. **Limitations in people with disabilities:** Several para swimmers with contractures around the hip and knee could not achieve standardised positioning for this test. Para swimmers with diplegic cerebral palsy often could not achieve full knee extension. One para swimmer with severe hip and knee contractures had to perform the test in a modified seated position with the ankle strap attached as the lower thigh.	

Supplementary Table 1 (continued). Description of isometric strength tests developed for Para swimming classification.

Test description	
Strength test: Hip flexion **Procedure:** Participants were in a supine position on a massage plinth with their legs off the bench at the popliteal crease. The tested leg was placed in an ankle cuff. The load cell attachment was positioned so that it was taut when the hip and knee of the tested leg were horizontal. Arms were folded across the chest, and the foot of the tested leg was not in contact with the strength rig. The load cell was zeroed before trials with participants leg in a relaxed position so that the load cell attachment was not taut. Participants were instructed to "take the slack" of the load cell attachment and pause prior to commencing the maximal effort test. **Rationale:** The leg kick contributes to propulsion and plays an important role in stabilising the body in coordination with the arm stroke during front crawl swimming. This test was designed to explain the contribution of kip and knee flexion to the drag and lift forces generated by the leg kick during front crawl. **Limitations in people with disabilities:** Several para swimmers with contractures around the hip and knee could not achieve standardised positioning for this test. Para swimmers with diplegic cerebral palsy often could not achieve full knee extension. One para swimmer with severe hip and knee contractures had to perform the test in a modified seated position with the ankle strap attached as the lower thigh.	

Supplementary online material

Supplementary Table 2. Strength test measures (mean ± SD) in non-disabled participants.

		Males (n=15)	Females (n=15)
Shoulder extension strength	Dominant (N)	194.3 (44.2)	117.0 (25.6)*
	Non-dominant (N)	184.7 (43.0)	113.4 (25.3)*
	Symmetry index	0.95 (0.03)	0.97 (0.02)
Shoulder flexion strength	Dominant (N)	152.3 (40.8)	79.2 (17.6)*
	Non-dominant (N)	142.9 (36.5)	74.0 (16.6)*
	Symmetry index	0.94 (0.03)	0.94 (0.05)
Hip extension strength	Dominant (N)	252.8 (42.8)	192.7 (34.6)*
	Non-dominant (N)	240.8 (37.3)	187.1 (36.0)*
	Symmetry index	0.95 (0.02)	0.92 (0.05)
Hip flexion strength	Dominant (N)	188.6 (46.2)	128.8 (14.9)*
	Non-dominant (N)	178.7 (43.1)	122.3 (14.0)*
	Symmetry index	0.95 (0.04)	0.95 (0.04)

* indicates significant difference ($p<0.01$) to male group.