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Journal article

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This is an Accepted Manuscript version of the following article, accepted for publication in *Journal of Sports Sciences*.

Hogarth, L., Nicholson, V., Spathis, J., Tweedy, S., Beckman, E., Connick, M., van de Vliet, P., Payton, C. and Burkett, B. (2019). A battery of strength tests for evidence-based classification in Para swimming. *Journal of Sports Sciences*, 37(4), pp. 404-413. <https://doi.org/10.1080/02640414.2018.1504606>.

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

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Running title: Strength impairment in Para swimming

Key words: disability, Paralympics, cerebral palsy, spinal cord injury, validity, reliability.

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|------------------------|------|
| Abstract word count: | 200 |
| Text-only word count: | 5018 |
| Tables and/or figures: | 5 |
| Supplementary tables: | 2 |

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Acknowledgements:

The authors would like to thank the participants for volunteering their time for this study. Also, the authors would like to acknowledge Jayden Lowrie, Samantha Yardy-Phelan, Hannah Jarvis and Ana Maia for their assistance in data collection. This research was supported by the International Paralympic Committee (IPC), UK Sport, Exercise & Sports Science Australia (Applied Sports Science Research Grant), and the University of the Sunshine Coast (Faculty Research Initiatives Grants Scheme). Mark Connick, Emma Beckman and Sean Tweedy are members of the IPC Classification Research and Development Centre (Physical Impairments), which is supported by the International Paralympic Committee.

20 INTRODUCTION

21 Classification plays an integral role in Paralympic sport and aims to promote increased
22 participation in sport by people with disabilities by minimising the impact that impairment
23 has on the competition outcome. Para swimming, one of the most popular Paralympic sports,
24 uses a functional classification system to group athletes with an eligible physical impairment.
25 Unfortunately, studies have shown current classification methods fail to delineate
26 performance between some classes and disadvantage athletes with certain types of physical
27 impairment within classes (Burkett et al., 2018; Daly & Vanlandewijck, 1999; Wu & Williams,
28 1999). The shortcomings of the current classification system may result, at least in part, from
29 issues with measurement weighting and aggregation stemming from a lack of understanding
30 of the relationship between impairment and swimming performance (Tweedy, Beckman, &
31 Connick, 2014). World Para swimming have mandated that research be conducted to provide
32 the scientific evidence to underpin a new classification system in Para swimming
33 (International Paralympic Committee, 2015).

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

45 Muscular strength and power are key determinants of success in competitive swimming and
46 their importance to propulsion during swimming is widely accepted (Crowley, Harrison &
47 Lyons, 2017; Loturco et al., 2016). Para swimmers with health conditions such as spinal cord
48 injury, cerebral palsy and Charcot-Marie-Tooth disease have impairments to the central and
49 peripheral nervous systems, musculoskeletal system or links between these structures, that
50 result in loss of muscular strength and power and affect their swimming performance
51 (Dingley, Pyne, & Burkett, 2014; Dingley, Pyne, Youngson & Burkett, 2015; Morouco et al.,
52 2011). Classifying strength impairment of Para swimmers with motor-complete spinal cord
53 injury is relatively straightforward as these athletes have a non-progressive loss of voluntary
54 motor control that corresponds to the level of lesion (Connick et al., 2018). Other progressive
55 and non-progressive medical conditions such as cerebral palsy, motor-incomplete spinal cord
56 injury, polio, and Charcot-Marie-Tooth disease have inconsistent clinical manifestations.
57 Para swimmers with these conditions have loss of voluntary motor control that varies
58 considerably for the severity of impairment and its presentation in the trunk, and upper and
59 lower limb extremities.

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

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

80 As isometric strength tests are limited in assessing muscular strength through full range of
81 motion, important steps in developing tests for classification include identifying the principal
82 muscle groups and actions that are involved in the sport (Beckman et al., 2017; Burkett et al.,
83 2017). Most studies in able-bodied swimmers have investigated front crawl swimming and
84 have reported the latissimus dorsi, pectoralis major, and teres minor play important roles in
85 stabilising and mobilising the shoulder into extension and adduction during the early and late
86 underwater pull phases that are primarily responsible for propulsion (Amaro, Morouco,
87 Marques, Fernandes & Marinho, 2017; Martens, Figueiredo & Daly, 2015). Agonist
88 antagonist activity of muscles of the elbow joint (i.e. biceps brachii and triceps brachii) and
89 wrist joint (i.e. brachioradialis, flexor carpi ulnaris, and extensor carpi ulnaris) stabilise the
90 forearm and hand to overcome water drag during these propulsive actions (Martens et al.,
91 2015).

92 Although the lower limb extremity contributes less to propulsion and swim velocity in front
93 crawl than the upper limb extremity (Amaro et al., 2017; Bartolomeu, Costa & Barbosa, 2018),

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

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

117

118 **METHODS**

119 **Participants**

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

133 **Design**

134 Isometric strength tests were developed by the research team consisting of experts in
135 evidence-based classification and Para swimming sport science. Tests were designed to
136 explain activity limitation in the freestyle discipline. They went through a development
137 process that included consultation with a panel of coaches, Para swimmers, classifiers,
138 administrators and sport science and medicine personnel, and were piloted in individuals
139 with disabilities. Para swimmers completed the test battery during organised data collection
140 events within Europe and Australia. They completed physical impairment and swimming-
141 specific assessments around their training schedules during these events. Non-disabled
142 participants and Para swimmers attended at least one 90-minute session where they
143 undertook the finalised test battery comprising four strength tests. Para swimmers also

144 attended a separate 30-minute session where their maximal freestyle swim performance
145 was assessed. Non-disabled participants were asked to maintain their usual exercise or
146 training regimes throughout their involvement in the study. Fifteen non-disabled
147 participants repeated the test battery within a week to examine the test-retest reliability of
148 strength tests.

149 **Experimental procedures**

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

160 The order of the strength tests was randomised. All participants undertook the test battery
161 under the instruction and supervision of the principal researcher. Isometric strength was
162 assessed using an S-type strain gauge attached to a custom-made aluminium frame that
163 provided force-time data collected at 200 Hz (Ergotest, Porsgrunn, Norway). The strength
164 test battery consisted of 4 tests that yielded 8 outcome measures: dominant and non-
165 dominant (i) shoulder extension strength, (ii) shoulder flexion strength, (iii) hip extension
166 strength and (iv) hip flexion strength. The strength test protocols are outlined in detail in
167 Supplementary Table 1. Following practice trials, participants performed 3 maximal effort
168 trials for each test. Once in position, participants were instructed to slowly build up their

169 applied force until reaching their maximal effort within 2-3 seconds. All contractions lasted
170 between 4 and 10 seconds and were performed on each minute, giving participants at least
171 50 seconds rest between consecutive trials (Beckman, Newcombe, Vanlandewijck, Connick,
172 & Tweedy, 2014). Each participant was given the same set of instructions before and during
173 contractions. The best trial indicated by the highest maximal voluntary contraction (MVC)
174 was used for analysis. For each strength test a symmetry index was calculated as a ratio of
175 their non-dominant to dominant limb strength.

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

189 **Statistical analyses**

190 Statistics were calculated using R version 3.4.0 (R Core Team, 2017). Shapiro-Wilks tests
191 indicated non-uniform distribution of several test measures for Para swimmers with
192 hypertonia or impaired muscle power. A Kruskal-Wallis rank test was used to determine
193 significant effects between hypertonia, impaired muscle power and non-disabled participant

194 groups. Wilcoxon tests were used post hoc to determine the source of significant effects,
195 with p-values adjusted for multiple comparisons using the Benjamini and Hochberg method.
196 Cliff's Delta (d), a non-parametric measure of effect size, was calculated with 95% confidence
197 intervals to indicate the magnitude of difference in strength test measures between Para
198 swimmers and non-disabled participants (Rogmann, 2013). Sex-specific differences were
199 calculated as there were significant differences found in isometric strength measures
200 between non-disabled male and female participants.

201 Random forest algorithm was used to establish the predictive validity of strength tests to
202 classify participants with and without strength impairment. Random forest is a non-linear
203 machine learning technique that uses an ensemble learning method for classification and
204 regression (Liaw & Wiener, 2002; Woods, Veale, Fransen, Robertson & Collier, 2018).

205 Separate models were built to determine the prediction accuracies based on sex. The
206 importance of predictor variables was determined using the mean decrease in accuracy,
207 which indicates the decrease in prediction accuracy that occurs when a single variable is
208 excluded during the out-of-bag error calculation (Liaw & Wiener, 2002; Woods et al., 2018).

209 Spearman correlation coefficients were calculated to assess the strength of association
210 between the Para swimmers' strength test measures and maximal clean swim speeds.

211 Correlations were calculated for the entire cohort of Para swimmers and independently for
212 the hypertonia and impaired muscle power groups. Significance was set at an alpha value of
213 ≤ 0.05 . The strength of correlations was interpreted as negligible (0.0-0.2), low (0.21-0.40),
214 moderate (0.41-0.60), high (0.61-0.80) and very high (>0.81) (Mukaka, 2012).

215 For non-disabled participants, normality of distribution was confirmed using the Shapiro-
216 Wilk test. Unpaired sample t-tests assuming equal variances were used to determine
217 differences between male and female participant groups. Reliability assessments were
218 calculated using Hopkins' reliability spreadsheet (Hopkins, 2015). Paired sample t-tests were

219 conducted to identify any systematic change in test measures between repeated trials. Intra-
220 class correlation coefficients (ICC) method 3,1, standard error of measurement (SEM) scores
221 expressed in the original units of measurement, and coefficient of variation (CV) scores were
222 calculated to provide an absolute assessment of reliability (Hopkins, 2000).

223

224 **RESULTS**

225 Differences in strength scores between Para swimmers and non-disabled participants are
226 shown in Figure 1. Para swimmers showed significantly lower strength scores for all tests,
227 except for shoulder flexion strength in female Para swimmers (Figure 1C and 1D) and
228 dominant hip flexion strength in male Para swimmers with hypertonia (Figure 1G). Para
229 swimmers showed larger differences in strength scores compared with non-disabled
230 participants for their non-dominant limbs (Figure 1). This was illustrated in differences
231 between non-disabled participants and Para swimmers for symmetry indexes calculated for
232 shoulder extension strength (mean \pm range = 0.96 ± 0.12 versus 0.82 ± 0.51 ; $d = 0.81$, $p < 0.01$),
233 shoulder flexion strength (mean \pm range = 0.94 ± 0.14 versus 0.84 ± 0.55 ; $d = 0.52$, $p < 0.01$),
234 hip extension strength (mean \pm range = 0.94 ± 0.16 versus 0.48 ± 0.99 ; $d = 0.77$, $p < 0.01$), and
235 hip flexion strength (mean \pm range = 0.95 ± 0.11 versus 0.49 ± 0.97 ; $d = 0.89$, $p < 0.01$).

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

241 Maximal clean swim speeds were 1.14 ± 0.34 m.s⁻¹ (range 0.21 to 1.62 m.s⁻¹) for male Para
242 swimmers and 1.03 ± 0.29 m.s⁻¹ (range 0.55 to 1.51 m.s⁻¹) for female Para swimmers. Para

243 swimmers with hypertonia ($1.19 \pm 0.27 \text{ m}\cdot\text{s}^{-1}$; range 0.55 to $1.62 \text{ m}\cdot\text{s}^{-1}$) had slightly faster clean
244 swim speeds than Para swimmers with Impaired muscle power ($1.00 \pm 0.35 \text{ m}\cdot\text{s}^{-1}$; range 0.21
245 to $1.51 \text{ m}\cdot\text{s}^{-1}$), although there was no significant difference found between groups ($p = 0.12$).
246 All strength scores had significant low to moderate correlations ($r=0.32$ to 0.53 , $p \leq 0.05$) with
247 maximal clean swim speed in the combined cohort of Para swimmers, except for non-
248 dominant shoulder flexion ($r=0.15$, $p=0.35$) (Figure 3).

249 There were fewer strength scores that had significant correlations with clean swim speeds
250 when hypertonia or impaired muscle power groups were analysed independently (Figure 3).
251 Dominant and non-dominant shoulder extension strength had the strongest correlations
252 with maximal clean swim speed for Para swimmers with hypertonia ($r=0.46$ to 0.66 , $p \leq 0.04$)
253 and impaired muscle power ($r=0.47$ to 0.51 , $p \leq 0.04$). Para swimmers with hypertonia also
254 showed significant correlations between clean swim speed and strength scores for dominant
255 shoulder flexion ($r=0.66$, $p < 0.01$) and dominant hip flexion ($r=0.44$, $p=0.05$), while there were
256 no correlations found for other strength tests ($r=0.27$ to 0.38 , $p=0.10$ to 0.25). Para
257 swimmers with impaired muscle power reported no significant correlations between clean
258 swim speed and strength scores for shoulder flexion ($r=-0.12$ to 0.12 , $p = 0.61$ to 0.63), hip
259 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).

260 Reliability assessments indicated all strength tests to be reliable in non-disabled participants
261 (Table 2). There were no significant changes in outcome measures between repeated trials,
262 with participants' absolute and relative changes ranging from $-7 \pm 4 \text{ N}$ to $2 \pm 18 \text{ N}$ and $-5 \pm$
263 10% to $3 \pm 12 \%$, respectively. Strength test measures in non-disabled participants are
264 shown in Figure 1 and Supplementary Table 2. Unpaired sample t-tests assuming equal
265 variances indicated significant differences ($p < 0.01$) between non-disabled male and female
266 participants for all strength tests, except for measures of strength symmetry.

267

268 DISCUSSION

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

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

289 Supporting the predictive validity of the isometric strength test battery, the random forest
290 algorithm had a 95 % success rate in correctly classifying participants with and without
291 physical impairment based on strength test measures. There were two Para swimmers that
292 were incorrectly classified as non-disabled participants. The first was a male Para swimmer

293 with hemiplegic cerebral palsy that competes in the S6 class based on classification of motor
294 coordination impairment, and so it is possible that that this participant is not affected by
295 strength impairment. For Para swimmers with hypertonia, the current classification system
296 assigns class based on the assessment of strength, motor coordination or range of movement
297 depending on which one of these is judged to be most affected by the Para swimmer's health
298 condition (International Paralympic Committee, 2017). It is interesting that all Para
299 swimmers with hypertonia in this study compete in their current sport class based on
300 assessment of motor coordination impairment. The high success rate of the random forest
301 in classifying these Para swimmers using isometric strength and symmetry scores indicates
302 that these Para swimmers have strength impairments that affect their swimming
303 performance (Figure 3). This finding highlights the complexity of these Para swimmers'
304 health conditions, and that classification should collectively account for impairments in
305 strength, motor coordination and range of motion for these swimmers.

306 The incorrect classification of the female Para swimmer by the random forest algorithm
307 raises several questions of the isometric strength test battery. This Para swimmer has an
308 incomplete L4-L5 spinal cord injury and competes in the S8 sport class at Paralympic and
309 World Championship standard. The random forest algorithm assigned 40 % of the votes to
310 the priori case most likely as the participant's strength scores were within or higher than the
311 lower and upper quartiles for scores in non-disabled females, except for dominant and non-
312 dominant hip extension. This highlights the requirement of obtaining normative values in
313 highly trained able-bodied swimmers to accurately infer strength impairment. Further, based
314 on their classification records the Para swimmer was most affected by limited strength
315 around the ankle joint. Active ankle range of motion is important to effectively orientate the
316 foot segment during leg kicking to generate drag and lift forces (Connaboy et al., 2016), and
317 plantar flexion at the ankle joint contributes to propulsion during starts and turns (Jones et
318 al., 2018; Morouco et al., 2012). Although active range of motion assessments might explain

319 part of this swimmer's activity limitation (Nicholson et al., 2018), these results indicate that
320 the isometric strength test battery is not entirely comprehensive.

321 An important aspect of this study was examining the convergent validity of isometric
322 strength tests by establishing their strength of association with freestyle swim performance.

323 When the entire para swimming cohort was included in analyses there were low to moderate
324 correlations found between maximal swim speed and all isometric strength scores, except

325 for non-dominant shoulder flexion (Figure 3). Para swimmers showed the strongest
326 correlations between isometric shoulder extension strength and maximal clean swim speed

327 (Figure 3A and 3B). The upper limb extremity contributes to most of the propulsive force
328 during tethered front crawl swimming (Amaro et al., 2017; Morouco et al., 2015), and the

329 shoulder position during this test represented the start of the underwater push phase where
330 able-bodied swimmers achieve the highest absolute hand speeds (Samson, Monnet, Bernard,

331 Lacouture & David, 2015). The lower limb extremity contributes less to propulsion in front
332 crawl swimming (Amaro et al., 2017; Morouco et al., 2015), which explains the lower

333 correlations found between hip flexion and extension strength and freestyle swim
334 performance in the combined cohort of Para swimmers (Figure 3). The leg kick is important

335 in stabilising and controlling body roll in coordination with the arm stroke (Bartolomeu et al.,
336 2018; Psycharakis & Sanders, 2010) and generates drag and lift forces that are likely to have

337 higher contributions to instantaneous swim velocity in cases where the arm stroke is limited
338 by impairment (Morouco et al., 2015; Bartolomeu et al., 2018). However, these tests might

339 not comprehensively describe knee flexion and plantar flexion strength impairments that
340 relate to starts and turns performance (Dingley et al., 2015; Jones et al., 2018) or propulsive

341 forces during swim kicking (Connaboy et al., 2016).

342 Ensuring that the isometric strength test battery is comprehensive and parsimonious is
343 important to consider before its implementation into a revised classification system. It is

344 important to highlight that there were fewer correlations found between strength scores
345 and maximal swim speeds when hypertonia and impaired muscle power groups were
346 analysed independently (Figure 3). There are two explanations for these results. First, the
347 wide range in location and distribution of strength impairment of Para swimmers that are
348 within these groups affect the ability of any singular strength score to explain activity
349 limitation in swimming. For instance, Para swimmers with impaired muscle power had a
350 range of medical conditions (Table 1), some that might cause an even distribution of strength
351 impairment across the upper and lower limbs (e.g. Charcot-Marie-Tooth disease) and others
352 where strength impairment is confined to the trunk and lower limbs (e.g. complete SCI).
353 Despite no correlation being found between lower limb strength and swim performance
354 within this group (Figure 3), lower limb strength scores might be useful in explaining activity
355 limitation in Para swimmers that have some remaining lower limb muscle power due to the
356 role of leg kick in controlling body roll and stabilising the torso (Bartolomeu et al., 2018;
357 Psycharakis & Sanders, 2010). Conversely, the assessment of trunk impairment might be
358 more important in understanding activity limitation in Para swimmers with complete SCI that
359 cannot leg kick due to having no lower limb muscle power (Altman et al., 2017; Altman et al.,
360 2018; Psycharakis & Sanders, 2010).

361 Another explanation for the above, is that the type of physical impairment influences the
362 association between strength tests and para swimming performance. It is interesting to note
363 that Para swimmers with hypertonia showed a high correlation between dominant shoulder
364 flexion and maximal clean swim speed ($r=0.66$, $p<0.01$), while there was no correlation found
365 in Para swimmers with impaired muscle power (Figure 3C). This test was included in the
366 battery as it was thought it would describe activity limitation in Para swimmers with severe
367 impairments that use modified swim strokes (Prins & Murata, 2008). The positioning and
368 action of the isometric shoulder flexion test is dissimilar to the kinematics of the underwater
369 and recovery stroke phases of front crawl in able-bodied swimmers (Martens et al., 2015),

370 which explains why no correlation was found with maximal swim speed in the impaired
371 muscle power group. Conversely, the shoulder flexion strength test might be associated with
372 the level of spasticity that affects Para swimmers with hypertonia and may be collinear with
373 reduced motor coordination and range of motion that affects swim performance. Indeed,
374 spasticity typically affects the flexor, adductor and internal rotator muscle groups more than
375 their antagonists (Antunes, Rossato, Lima Kons, Luiz Sakugawa & Fischer, 2017; Delgado &
376 Albright, 2003), and there is a high inverse association between the level of spasticity and
377 voluntary motor function in people with health conditions such cerebral palsy and acquired
378 brain injury (Delgado & Albright, 2003). These results highlight the impairment-specific
379 nature of activity limitation in Para swimming, and that separate test batteries could be used
380 to classify Para swimmers based on their aetiology of impairment.

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

391 It is important to note that the application of this study's findings is limited without further
392 research. This study intentionally limited tests that were designed to explain activity
393 limitation in the freestyle discipline as there was limited time available to test Para swimmers.
394 While there is likely to be some crossover between tests, other swim strokes are dependent

395 on muscle groups and actions that were not assessed in this study (Martens et al., 2015).
396 Targeted efforts are now required to develop strength tests that explain activity limitation in
397 other swim strokes. Once this has been achieved, data collection in a larger sample of para
398 swimmers can be conducted to define the relative impact that strength impairments have
399 on swimming performance and guide valid classification structures (Altman et al., 2018;
400 Connick et al., 2018; Hogarth, Payton, Van de Vliet, Connick & Burkett, 2018).

401 The isometric strength tests in this study also have several inherent limitations in classifying
402 strength impairment. Namely, they are susceptible to athletes misrepresenting their abilities,
403 they limit strength assessment to a fixed range of motion, strength scores might be
404 susceptible to fatigue induced by prior activity or the tests themselves, and measures might
405 be responsive to sport-specific training regimes (McGuigan, Newton, Winchester & Nelson,
406 2010). Even with these limitations, the objective measurement of strength impairment will
407 undoubtedly improve the accuracy and transparency of Para swimming classification
408 compared with current methods (Connick et al., 2018). Additionally, longitudinal
409 assessments of isometric strength in Para swimmers will provide insights into their
410 responsiveness to sport-specific training regimes so that classifiers can more accurately infer
411 strength impairment, and machine learning algorithms can predict competitive
412 performances from objective impairment measures to identify outlying performances
413 caused by intentional misrepresentation of abilities (Hogarth et al., 2018).

414

415 **CONCLUSIONS**

416 This study presented isometric strength tests that were developed to permit evidence-based
417 classification in Para swimming. Strength test measures had acceptable reliability in non-
418 disabled participants - a requisite of evidence-based classification. Differences in strength
419 test measures were found between non-disabled participants and Para swimmers with

420 hypertonia or impaired muscle power, and random forest algorithm successfully classified
421 95% of Para swimmers. These results indicate that these tests will be useful in inferring loss
422 of strength in Para swimmers with strength impairment and guiding minimum eligibility
423 criteria. Dominant and non-dominant strength scores also had significant correlations with
424 maximal freestyle swim speed in Para swimmers. This suggests that strength tests will be
425 useful in explaining activity limitation in Para swimming, although results indicate that the
426 type and aetiology of physical impairment influence the utility of some strength tests.
427 Collectively, the results of this study make a significant contribution toward evidence-based
428 methods of classification for Para swimmers with strength impairments.

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Figure captions

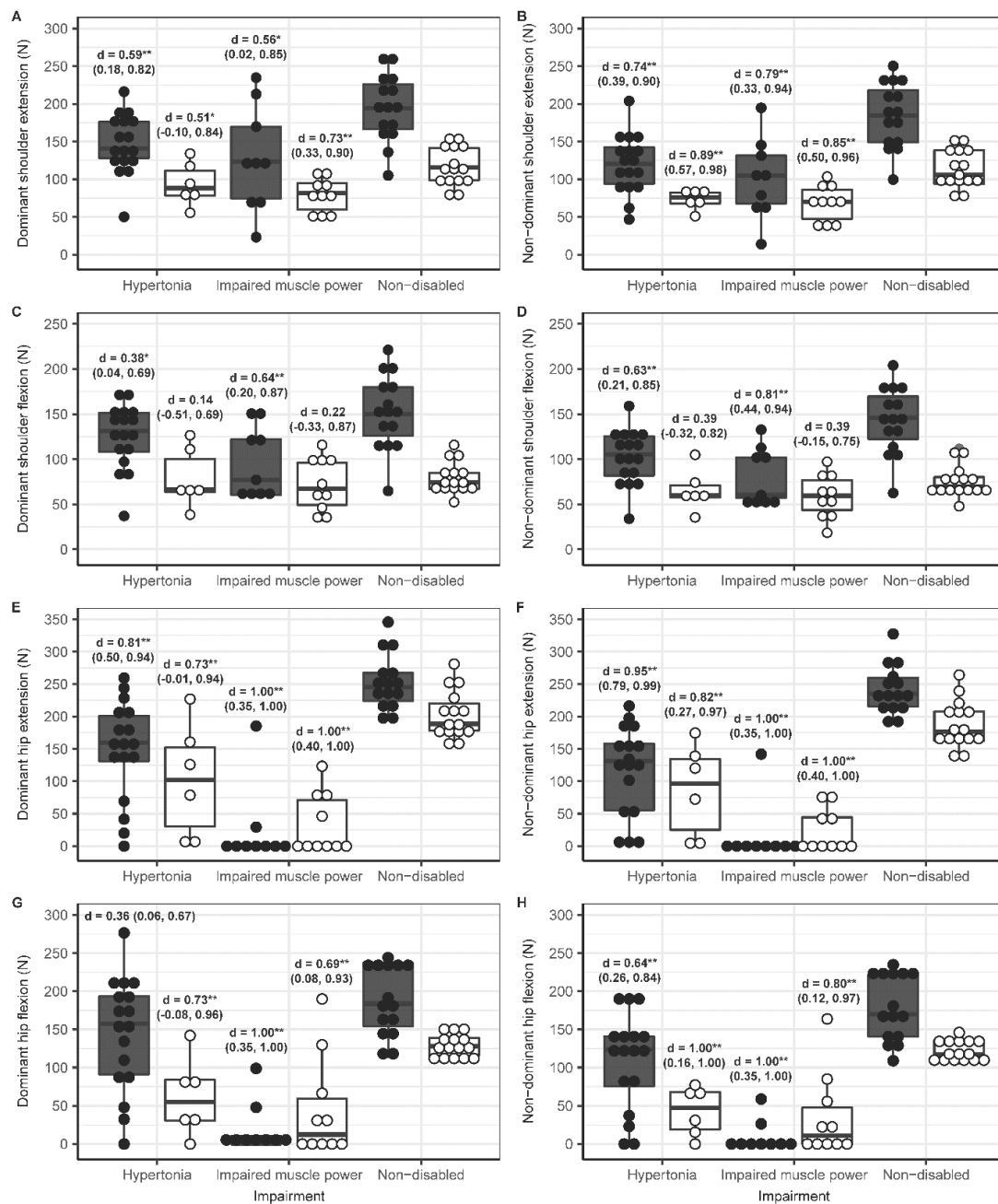


Figure 1. Strength test scores for Para swimmers with physical impairments and non-disabled participants. Scores a for (A) dominant and (B) non-dominant shoulder extension, (C) dominant and (D) non-dominant shoulder flexion, (E) dominant and (F) non-dominant hip extension, and (G) dominant and (H) non-dominant 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. *($p \leq 0.05$) and **($p \leq 0.01$) indicate significance.

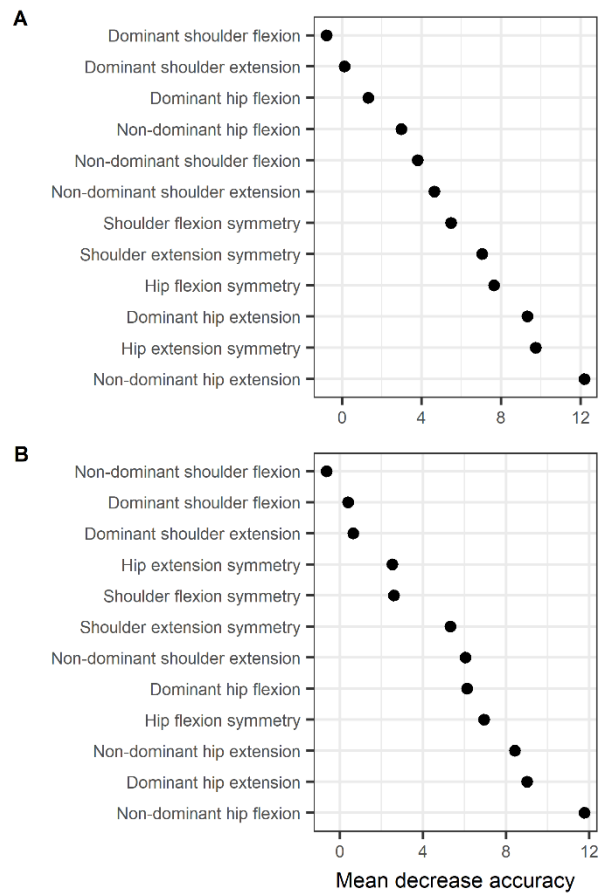


Figure 2. Mean decrease in accuracy scores indicating variable importance in classifying participants with and without physical impairment. Scores are reported for (A) male and (B) female participants. The variable importance score is the decrease in accuracy for each predictor variable when it is excluded 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.

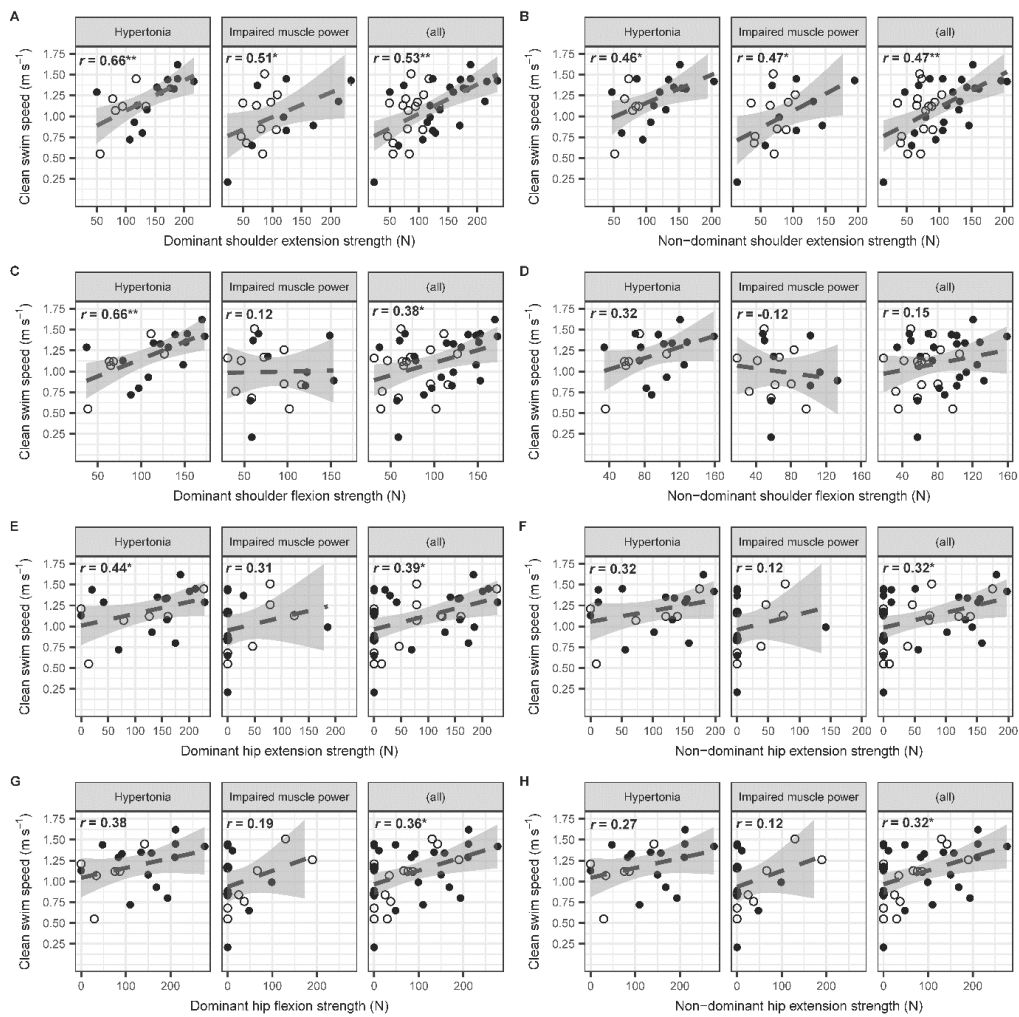


Figure 3. Strength of association between strength test scores and clean swim speed during maximal freestyle swimming. Data are Spearman correlation coefficients indicating strength of association between clean swim speed and (A) dominant and (B) non-dominant shoulder extension, (C) dominant and (D) non-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 | |
|---|---|
| <p>Strength test: Shoulder extension</p> <p>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.</p> <p>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.</p> <p>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.</p> |  |


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

| Test description | |
|---|---|
| <p>Strength test: Shoulder flexion</p> <p>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.</p> <p>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.</p> <p>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.</p> |  |

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

| Test description | |
|---|---|
| <p>Strength test: Hip extension</p> <p>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.</p> <p>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.</p> <p>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.</p> |  |

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

| Test description | |
|--|---|
| <p>Strength test: Hip flexion</p> <p>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.</p> <p>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.</p> <p>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.</p> |  |

Supplementary online material

Supplementary Table 2. Strength test measures (mean \pm 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.