Title: Classifying motor coordination impairment in Para swimmers with brain injury

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Abstract

Objectives: The International Paralympic Committee has mandated that International Sport Federations develop sport-specific classification systems that are evidence-based. This study examined the predictive and convergent validity of instrumented tapping tasks to classify motor coordination impairments in Para swimming.

Design: Cross-sectional.

Method: Thirty non-disabled participants and twenty-one Para swimmers with brain injury completed several instrumented tapping tasks as an assessment of upper and lower limb motor coordination. Para swimmers also completed a maximal freestyle swim to obtain a performance measure. The predictive and convergent validity of instrumented tapping tasks was examined by establishing differences in test measures between participants with and without brain injury and defining the strength of association between test measures and maximal freestyle swim speed in Para swimmers, respectively.

Results: Random forest successfully classified 96% of participants with and without brain injury using test measures derived from instrumented tapping tasks. Most test measures had moderate to high correlations ($r = 0.54$ to 0.72; $p < 0.01$) with maximal freestyle swim speed and collectively explained up to 72% of the variance in maximal freestyle swim performance in Para swimmers with brain injury.

Conclusions: The results of this study evidence the predictive and convergent validity of instrumented tapping tasks to classify motor coordination impairments in Para swimmers with brain injury. These tests can be included in revised Para swimming classification to improve the objectivity and transparency in determining athlete eligibility and sport class for these Para athletes.

Keywords: Paralympic; Sports for Persons with Disabilities; Swimming; Freestyle; Classification; Cerebral Palsy.

Introduction

Swimming is one of the inaugural Paralympic sporting events and includes athletes with physical, visual and intellectual impairment. Distinguishing Paralympic events from their Olympic counterparts are classification systems that are used to minimise the impact of impairment on the competition outcome. Para swimming has used a functional classification system to classify athletes with physical impairment since the 1992 Barcelona Paralympic games. The effectiveness and fairness of the system has since been questioned.[1-3] This has prompted World Para Swimming, the international federation that governs the sport, to establish international research projects to provide the scientific evidence that underpins a new classification system in Para swimming.

Some of the most challenging cases in Para swimming classification are those athletes with congenital or acquired brain injury (e.g. cerebral palsy). These athletes have injury to the pyramidal or extrapyramidal tracts of the brain that causes altered efferent output and effects neuromuscular function.[4] The clinical features presented by athletes with brain injury include decreased central motor output, hypertonia, incoordination and coactivation of agonist and antagonist muscle groups, although the distribution and severity of these features varies considerably depending on the aetiology of brain injury.[4] Research has provided some understanding of how these clinical features impact on sport and exercise performance,[5-7] with performance deficits being attributed to losses in strength,[8 9] joint range of motion[10] and motor coordination.[11]

Motor coordination, which is defined as the ability to produce skilled movement fluidly, rapidly and accurately is affected in Para athletes with brain injury.[4 10] It is yet to be reported how swim performance is affected by motor coordination impairment. Swimming speed is fundamentally dependent on stroke length and stroke rate, increasing either one of these determinants whilst maintaining the other will increase swim speed.[12 13] Motor coordination impairment could limit stroke length and stroke rate in several ways. For instance, injury to the basal ganglia causes decreased central motor output and control of antagonist muscles that might affect hand speeds during the above and underwater stroke phases and limit stroke rate;[14] and injury to the cerebellum can affect inter-limb coordination and postural control causing inefficient stroke patterns.[15]

The assessment of motor coordination in current Para swimming classification lacks many of the key measurement properties required for evidence-based classification.[16] Para swimmers with hypertonia, ataxia and athetosis may undertake several dry-land tests that assess their ability to ‘coordinate’ their limbs during repetitive single-joint swimming actions (e.g. shoulder flexion and extension) that are performed at a steady pace and of increasing speed.[17] Para swimmers are given a score from 0 to 5 for each joint based on subjective assessment of the movement, such as “…moderate range of movement, moderate spasticity with time restricting movement and/or moderate coordination problems…” for a score of 3.[17] While the classifiers conducting these tests are experts and this is current best practice, these tests are not suitable for evidence-based classification as they have a high dependence on clinical judgment and provide only ordinal-scale measures that are limited when quantifying the relationship between impairment and performance.[16]

Previous research has developed instrumented tapping tasks that might provide valid methods of assessing motor coordination impairment for Para sport classification.[10,18] Reciprocal and discrete tapping tasks that are specific to running, throwing and wheelchair sports have been shown to be reliable in non-disabled participants, and provide ratio-scale measures that discriminate between Para athletes and non-disabled participants.[10,18] Further, the difficulty of tapping tasks can be manipulated to detect intentional misrepresentation of abilities by evaluating conformity with Fitts’ law.[19] Despite these promising results, there is limited evidence to suggest that they have a meaningful association with sport performance and no such work has been undertaken in swimming.[10,11]

The aims of this study were to: (i) examine the predictive validity of instrumented tapping tasks to discriminate between participants with and without brain injury, and (ii) establish the convergent validity of instrumented tapping tasks by defining their strength of association with swim performance in Para swimmers with brain injury. If tests are found to discriminate between participants with and without brain injury and explain activity limitation in swimming, then they will likely have utility in a revised Para swimming classification system.

Methods

Data were collected from 51 participants including Para swimmers with congenital or acquired brain injury and non-disabled participants (Table 1). Para swimmers had received national or international classification and were undertaking planned training regimes at the time of testing. Non-disabled participants were between the ages of 18 and 35 years of age and were undertaking planned exercise, training or competition at least twice a week for a minimum of 80 minutes. All participants gave written informed consent under approved ethical guidelines from institutional human research ethics committees (100517ESSHJ and A16892).

Participants completed a questionnaire regarding demographics, their typical training regime (mode, frequency and duration 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 obtained from classification records listed in the IPC Sports Data Management System (https://db.ipc-services.org/sdms). Participant's stature and body mass were recorded prior to testing. Stature was estimated from sitting height recorded from a custom-built chair for Para swimmers with no or poor locomotor ability.[17]

Motor coordination was assessed with novel tapping tasks using custom-made wireless tapping pads (Ergotest, Porsgrunn, Norway). The tapping pads, which consisted of resistive touch panels that provided a 0.195 m x 0.10 m target, were connected to a personal computer via Bluetooth connection with a Muscle Lab data synchronisation unit (Ergotest, Porsgrunn, Norway). The tapping pads were positioned with a 0.195 m distance between their centres. Participants completed four motor coordination tests: (i) bilateral upper limb tapping, (ii) dominant and non-dominant upper limb tapping, (iii) bilateral lower limb tapping and (iv) dominant and non-dominant lower limb tapping. The test protocols are outlined in Supplementary Material Appendix 1. Tests involved the participants completing as many cycles as possible within 15 s test duration. Participants were instructed to tap as rapidly and accurately as possible between the two pads. They commenced the tests on their own time and an audio signal was used to notify participants of the end of the test. Following a minimum of one practice trial, participants completed three trials for each test. **Participants were given at least 45 s rest between consecutive trials.** Trials were deemed successful if above 90% accuracy was achieved. All trials were recorded using a tripod mounted video camera to verify the number and accuracy of contacts. The best trial, indicated by the lowest mean movement time (MMT), was used for analysis. Three Para swimmers with diplegic cerebral palsy were unable to complete the lower limb tapping tasks due to severe spasticity in the lower limbs. To provide a ratio-scale score, these participants were given a score representing one complete cycle (15 000 ms) for these tests.

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.

Statistical analyses were conducted using R version 3.4.1 (R Core Team, 2017). Test measures were log-transformed for analysis. **The Shapiro-Wilk test indicated most variables had non-uniform distribution and so non-parametric techniques were used for analysis.** Wilcoxon rank tests were used to identify differences between non-disabled participants and Para swimmers. Cliff's delta (d) was calculated with 95% confidence intervals to indicate the magnitude of group differences. **The magnitudes of d scores were evaluated as negligible (<0.147), small (0.147-0.33), medium (0.33-0.474), or large (>0.474).[20]** Male and female participants were pooled for analysis as there was no effect of sex found in the non-disabled participant group. Random forest algorithm was used to further examine the predictive validity of motor coordination tests in discriminating between participants with and without brain injury. Random forest is a non-linear machine learning technique that uses an ensemble learning method for classification and regression. Details on the random forest analysis are shown in Supplementary Material Appendix 3.

Spearman correlation coefficients were calculated to assess the strength of association between log-transformed test measures and Para swimmers' maximal freestyle swim speeds. An alpha value of 0.05 was used to indicate a significant association. 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 (>0.80).[21] Test measures that were found to have a significant association with freestyle swim speed were included in ensemble partial least squares regression as dependent variables. Details on model training, internal cross validation and feature selection methods used in partial least squares regression are shown in Supplementary Material Appendix 4.

Results

The results of instrumented tapping tasks in non-disabled participants and Para swimmers with brain injury are shown in Supplementary Material Appendix 2. Test measures were found to be reliable in a subsample of 15 non-disabled participants (Supplementary Material Table S2). Wilcoxon rank tests showed significant differences ($p < 0.01$) in all test measures between Para swimmers and non-disabled participants (Figure 1), with larger differences reported for non-dominant limb tapping (d = 0.93 to 0.99) compared with dominant limb tapping (d = 0.78

to 0.82). Random forest algorithm, that included test measures as predictor variables, successfully classified 96% of participants with and without brain injury (out-of-bag [OOB] error estimate = 3.92%). The rank importance of predictor variables, and ratio of votes assigned for individual cases are shown in Supplementary Material Appendix 3.

All test measures had significant correlations with maximal freestyle swim speed, except for bilateral upper limb tapping, **upper limb symmetry score, and lower limb symmetry score** (Figure 2). Supplementary Material Appendix 4 shows the prediction accuracy and error, internal cross validation, and importance of predictor variables for partial least squares regression. Dominant upper limb tapping, nondominant upper limb tapping, and bilateral lower limb tapping were the most important predictors of maximal freestyle swim speed and showed the best prediction accuracy (R^2 = 0.724, RMSE = 0.184) and stability (cvR^2 = 0.675, cvRMSE = 0.199) when included in partial least squares regression.

Discussion

Para athletes with congenital or acquired brain injury present some of the most challenging cases in Para swimming classification. The development of valid tests of strength, range of motion and motor coordination is a key research objective that is required to guide an evidence-based classification system for these Para athletes.[22 23] This study found instrumented tapping tasks to be valid tests of motor coordination impairment that can be included in a revised Para swimming classification system.

Eligibility in Para sport is determined by the type of impairment and whether the severity of impairment conforms with the minimum eligibility criteria.[16] Para swimmers with brain injury have one or a combination of hypertonia, ataxia and athetosis, all of which can result in loss of motor coordination that might affect swimming performance. The instrumented tapping tasks presented in this study were able to differentiate between participants with and without brain injury (Figure 1). This result shows that the Para swimmers in this study did in fact have impaired motor coordination, and that the instrumented tapping tasks provide useful assessments to infer the extent of motor coordination impairment resulting from brain injury.

In support of the above, test measures successfully classified 96% of participants with and without brain injury using random forest algorithm (Supplementary Material Appendix 3). The ensemble learning method used during random forest allows the probability of classification to be attained, which could be useful for determining athlete eligibility. For example, two Para swimmers were incorrectly classified as non-disabled participants by random forest algorithm, suggesting they have similar motor coordination to non-disabled participants. On further inspection it is apparent that there was a degree of uncertainty in the classification assigned by the random forest model as approximately 35% of the votes were allocated to the priori case for both Para swimmers (i.e. the Para swimmers were assigned to the correct class 35% of the time). These Para swimmers had mild or moderate hemiplegic cerebral palsy, and although they might have achieved similar scores to non-disabled participants in some tapping tasks, it is evident that they have some loss of motor coordination in their non-dominant limbs when comparing their upper (0.64 and 0.79) and lower limb (0.71 and 0.89) symmetry scores with non-disabled participants (upper limb = 0.88±0.05 and lower limb = 0.94±0.07). These findings highlight the potential of using ratio-scale measures to improve the objectivity and transparency of athlete eligibility in Para swimming, particularly as most test measures were related to freestyle swimming performance (Figure 2). Classification models that are trained in Para swimming cohorts with more homogenous impairment location and distribution (e.g. hemiplegic versus diplegic) might improve the accuracy of these models to better guide athlete eligibility.

An important measurement property of impairment tests used in classification is that they explain activity limitation in the sport of interest.[16] All motor coordination test measures, except for bilateral upper limb tapping **and symmetry scores**, were found to have moderate to large correlations with maximal freestyle swim speed (Figure 2). These test measures also explained 72.4% of the variance in swim performance when included in partial least squares regression.

These results evidence the convergent validity of the instrumented tapping tasks in Para swimming classification.

In agreement with previous research,[23 24] motor coordination tests relevant to the upper limbs were found to be more important predictors of freestyle swim speed than lower limb test performance (Supplementary Material Figure S4). Indeed, the upper limbs contribute most of the propulsive force during freestyle swimming,[25] and motor coordination impairment of the upper limbs might impact on hand speeds during the above and underwater stroke phases and inter-arm coordination associated with propulsion and propelling efficiency.[14 15 26] It is interesting that lower limb tapping tasks had moderate to high correlations ($r = -0.57$ to -0.62, $p < 0.01$) with maximal swim speed contrasting with no or low correlations ($r = 0.27$ to 0.44) that have been reported previously for lower limb strength tests in a similar cohort of Para swimmers.[23] This infers that lower limb coordination is more important than lower limb strength in freestyle swimming. Although the lower limbs contribute less to propulsion than the upper limbs in freestyle, leg-to-arm coordination might impact on the propulsion and propelling efficiency of the upper limbs,[26 27] or motor coordination impairment in the lower limbs could be collinear with reduced range of motion that causes a poor streamline position and increased form drag.[22 28]

Despite the more similar action of the bilateral upper limb tapping task to freestyle swimming than unilateral tasks, this test was found to have no association with freestyle swim speed (Figure 2a). This might be explained by different strategies that were used by participants during this test; although they were instructed to maintain extended arms to encourage movement at the shoulder joint, participants adopted tapping strategies that involved movements at the shoulder, wrist and/or finger joints. Further, the larger correlation found for dominant upper limb tapping compared with nondominant upper limb tapping suggests that Para swimmers with a relatively unaffected dominant limb might be able to compensate more effectively for the activity limitation caused by the more affected limb. Similar findings have been reported for strength and range of motion impairment in swimming,[23] cycling,[29] and running.[9 10]

The results of this study support the use of instrumented tapping tasks to derive valid classification structures for Para swimmers with brain injury. **Further research that establishes the relationship between motor coordination tests and performance in the other swim strokes will confirm their utility in Para swimming classification.** Cluster analysis of test measures can derive classes of Para swimmers with similar location, severity and/or distribution of motor coordination impairment,[30 31] or an independent measure of estimated activity limitation that is derived from test measures can be used to assign classification.[24] However, it is likely that strength and range of motion impairment also explain activity limitation in Para swimmers with brain injury.[22 23] In the only other study to establish the impact of physical impairment on Para swimming performance, measures of limb length were found to explain 80% of the variance in 100 m freestyle performance in Para swimmers with limb deficiency.[24] It is interesting then that motor coordination test measures were found to account for 72% of the variance in swim performance in this study, despite the absence of measures related to strength and range of motion that are affected by brain injury. This could be explained by the fact that most Para swimmers had hypertonia, and severity of motor coordination impairment might be collinear with strength and range of motion impairment within this group.[32] Indeed, partial least squares regression considerably underestimated swim performance ($-0.44\ m{\cdot}s^{-1}$) for one Para swimmer with athetosis who would predominately be affected by motor coordination impairment. This suggests that motor coordination, strength and range of motion tests should be used concurrently to guide classification of Para swimmers with brain injury. **Further research in a larger cohort of Para swimmers, including those with dyskinesia (i.e. athetosis and dystonia) and ataxia, is required to establish the impact these impairments have on swimming performance.**

Conclusion

The development of valid tests of impairment is one of the key challenges in guiding the development of evidence-based classification systems in Para sport. This study showed instrumented tapping tasks that were reliable in non-disabled participants, were able to discriminate between participants with and without brain injury and explained most of the variance in maximal freestyle swim performance in Para swimmers with brain injury. These results evidence the predictive and convergent validity of instrumented tapping tasks to classify motor coordination impairments in Para swimmers with brain injury. Future research that establishes the relative impact of strength, range of motion and motor coordination on Para swimming performance is required to help guide evidence-based classification structures for these Para athletes.

Practical implications

- Instrumented tapping tasks can be used to infer loss of motor coordination resulting from brain injury and determine athlete eligibility in Para swimming.
- These tapping tasks provide an objective estimate of activity limitation in Para swimming resulting from motor coordination impairment and can be used to assign sport class.
- A revised Para swimming classification system due to be implemented following the 2020 Tokyo Paralympic games can include these tapping tasks to improve the objectivity and transparency of athlete classification.

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Tables

Table 1. Characteristics of non-disabled participants and Para swimmers with brain injury.

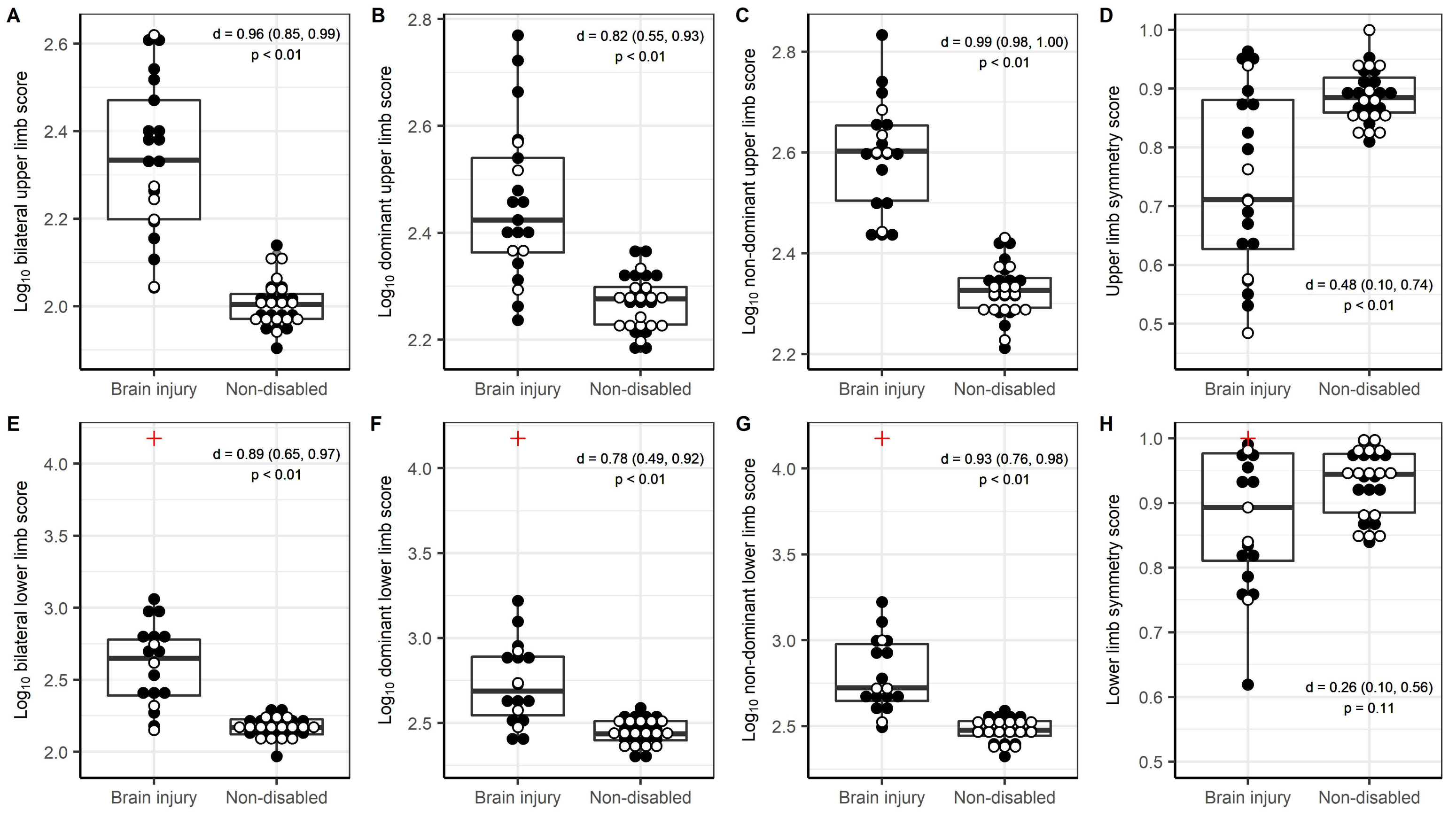
		Para swimmers with brain injury	Non-disabled participants
	Males	n = 16	n = 15
	Females	n = 5	n = 15
Age (yrs)	Males	28.2 (6.8)	23.5 (4.1)
	Females	20.0 (4.5)	23.3 (4.5)
Body mass (kg)	Males	68.7 (9.9)	79.8 (11.4)
	Females	59.0 (11.3)	68.1 (9.7)
Stature (cm)	Males	171.2 (11.7)	182.7 (7.7)
	Females	160.9 (10.0)	171.4 (7.0)
Reported exercise frequency (n/week)		Median = 7 Range = 2 to 15	Median = 6 Range = 3 to 14
Accumulated exercise duration (min/week)		Median = 525 Range = 180 to 1200	Median = 360 Range = 150 to 1200
Reported activities		Competitive swimming (n=21) Resistance training (n=15)	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=7) National (n=14)	
Competitive swim experience (yrs)		Median = 9.5 Range = 3 to 26	
S Class		S3 (n=1) S4 (n=5) S5 (n=1) S6 (n=6) S7 (n=2) S8 (n=4) S9 (n=2)	
Medical conditions		Diplegic, spastic (n=8) Hemiplegic, spastic (n=7) Quadriplegic, spastic (n=3) Quadriplegic, mixed (n=1) Quadriplegic, Athetoid (n=1) Other (n=1)	

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, **Australian rules football (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 at a Paralympic or World Championship event.

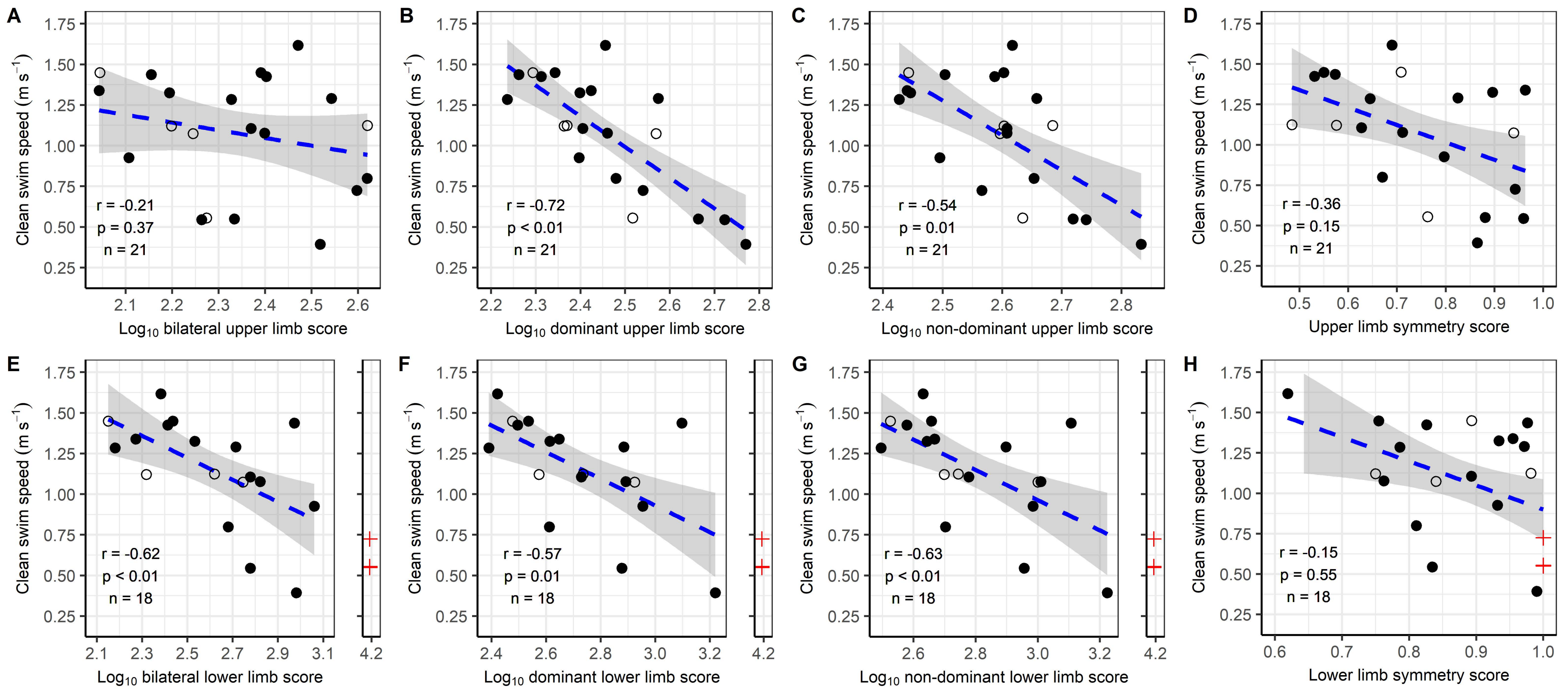
Figure legends

Figure 1. Test measures for instrumented tapping tasks in non-disabled participants and Para swimmers with brain injury. Data are Cliff's delta with 95% confidence interval and p values derived from Wilcoxon rank tests showing differences between non-disabled participants and Para swimmers for (A) bilateral upper limb tapping, (B) dominant upper limb tapping, (C) non-dominant upper limb tapping, **(D) upper limb symmetry score,** (E) bilateral lower limb tapping, (F) dominant lower limb tapping, (G) non-dominant upper limb tapping, and **(H) lower limb symmetry score.** Data are reported for male (dark points) and female (white points) participants, and outlying participants (**crosses)** that could not complete the lower limb tapping tasks due to severe spasticity.

Figure 2. Strength of association between motor coordination test measures and maximal freestyle swim speed in Para swimmers with brain injury. Data are Spearman correlation coefficients for (A) bilateral upper limb tapping, (B) dominant upper limb tapping, (C) non-dominant upper limb tapping, **(D) upper limb symmetry score,** (E) bilateral lower limb tapping, (F) dominant lower limb tapping, (G) non-dominant upper limb tapping, and **(H) lower limb symmetry score.** Data are reported for male (dark points) and female (white points) Para swimmers, and outlying participants (crosses) that have been removed from analysis due to severe lower limb spasticity.



A
d = 0.96 (0.85, 0.99)
p < 0.01
Log10 bilateral upper limb score
2.0
2.2
2.4
2.6
Brain injury
Non-disabled
B
d = 0.82 (0.55, 0.93)
p < 0.01
Log10 dominant upper limb score
2.2
2.4
2.6
2.8
Brain injury
Non-disabled
C
d = 0.99 (0.98, 1.00)
p < 0.01
Log10 non-dominant upper limb score
2.2
2.4
2.6
2.8
Brain injury
Non-disabled
D
d = 0.48 (0.10, 0.74)
p < 0.01
Upper limb symmetry score
0.5
0.6
0.7
0.8
0.9
1.0
Brain injury
Non-disabled
E
d = 0.89 (0.65, 0.97)
p < 0.01
Log10 bilateral lower limb score
2.0
2.5
3.0
3.5
4.0
Brain injury
Non-disabled
F
d = 0.78 (0.49, 0.92)
p < 0.01
Log10 dominant lower limb score
2.5
3.0
3.5
4.0
Brain injury
Non-disabled
G
d = 0.93 (0.76, 0.98)
p < 0.01
Log10 non-dominant lower limb score
2.5
3.0
3.5
4.0
Brain injury
Non-disabled
H
d = 0.26 (0.10, 0.56)
p = 0.11
Lower limb symmetry score
0.5
0.6
0.7
0.8
0.9
1.0
Brain injury
Non-disabled



A
r = -0.21
p = 0.37
n = 21
Log10 bilateral upper limb score
B
r = -0.72
p < 0.01
n = 21
Log10 dominant upper limb score
C
r = -0.54
p = 0.01
n = 21
Log10 non-dominant upper limb score
D
r = -0.36
p = 0.15
n = 21
Upper limb symmetry score
E
r = -0.62
p < 0.01
n = 18
Log10 bilateral lower limb score
F
r = -0.57
p = 0.01
n = 18
Log10 dominant lower limb score
G
r = -0.63
p < 0.01
n = 18
Log10 non-dominant lower limb score
H
r = -0.15
p = 0.55
n = 18
Lower limb symmetry score
Clean swim speed (m s−1)

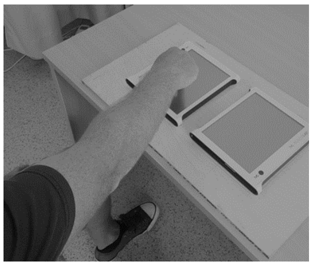
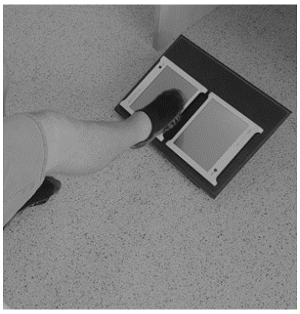
Classifying motor coordination impairment in Para swimmers with brain injury

Supplementary Material

Contents

Supplementary Material Appendix 1

Table S1. Test description of instrumented tapping tasks.

Test	Description	
Bilateral upper limb tapping	Participants were seated in an upright position with a back-rest for support. The mid-line of the participant was positioned in line with the middle of the two tapping pads that were secured to a table in front of the participant. The Participant extended their arms with their hands in a fist and their index finger extended, and the two pads were secured to the table so that the left and right index finger were positioned in the centre of the tapping pads. With their arms extended, participants were instructed to alternate tapping between the two pads using their left and right index fingers as quickly and as accurately as possible. The target area of tapping pads was 0.195 m x 0.10 m and were positioned with a 0.195 m distance between centres (Index of difficulty = 0.96).	
Unilateral upper limb tapping	Participants were seated in an upright position with a back-rest for support. The mid-line of the participant was positioned in line with the middle of the two tapping pads that were secured to a table in front of the participant. The Participant extended their arms with their hands in a fist and their index finger extended, and the two pads were secured to the table so that the left and right index finger were positioned in the centre of the tapping pads. With the tested arm extended, participants were instructed to alternate tapping between the two pads using their index finger as quickly and as accurately as possible. The non-tested arm was rested on the participants thigh. The target area of tapping pads was 0.195 m x 0.10 m and were positioned with a 0.195 m distance between centres (Index of difficulty = 0.96).	
Bilateral lower limb tapping	Participants were seated in an upright position with a back-rest for support. The mid-line of the participant was positioned in line with the middle of the two tapping pads that were secured to a footrest with a 30° incline in front of the participant. The Participant extended their legs at the knee and ankle, and the two pads were secured to the footrest so that the left and right big toe were positioned in the centre of the tapping pads. With their legs extended, participants were instructed to alternate tapping between the two pads using their left and right big toe as quickly and as accurately as possible. The target area of tapping pads was 0.195 m x 0.10 m and were positioned with a 0.195 m distance between centres (Index of difficulty = 0.96).	
Unilateral lower limb tapping	Participants were seated in an upright position with a back-rest for support. The mid-line of the participant was positioned in line with the middle of the two tapping pads that were secured to a footrest with a 30° incline in front of the participant. The Participant extended their legs at the knee and ankle, and the two pads were secured to the footrest so that the left and right big toe were positioned in the centre of the tapping pads. With their tested leg extended, participants were instructed to alternate tapping between the two pads using their big toe as quickly and as accurately as possible. The non-tested leg was relaxed with the foot positioned outside of the tapping pads on a stable surface. The target area of tapping pads was 0.195 m x 0.10 m and were positioned with a 0.195 m distance between centres (Index of difficulty = 0.96).	

Supplementary Material Appendix 2

Test measures in Para swimmers and non-disabled participants

Table S2. Test measures in non-disabled participants and Para swimmers with brain injury.

	Para swimmers with brain injury			Non-disabled participants		
	Combined (n=21)	Males (n=16)	Females (n=5)	Combined (n=30)	Males (n=15)	Females (n=15)
Bilateral upper limb tapping (ms)	237 (98)	245 (93)	210 (119)	102 (13)	101 (14)	104 (13)
Dominant upper limb tapping (ms)	302 (111)	311 (121)	272 (74)	187 (13)	192 (28)	183 (16)
Non-dominant upper limb tapping (ms)	404 (102)	406 (111)	398 (76)	213 (22)	216 (28)	211 (24)
Upper limb symmetry score	0.74 (0.15)	0.76 (0.15)	0.69 (0.18)	0.88 (0.06)	0.89 (0.04)	0.87 (0.07)
Bilateral lower limb tapping (ms)	627 (457)	647 (443)	564 (548)	149 (24)	153 (29)	146 (19)
Dominant lower limb tapping (ms)	744 (469)	755 (479)	712 (487)	285 (48)	291 (57)	279 (39)
Non-dominant lower limb tapping (ms)	815 (447)	826 (454)	778 (473)	302 (46)	305 (53)	300 (40)
Lower limb symmetry score	0.88 (0.11)	0.88 (0.11)	0.89 (0.10)	0.96 (0.07)	0.95 (0.08)	0.93 (0.06)

Data are mean (standard deviation) of the raw test measures. Lower tapping times (ms) represent faster tapping speeds. Upper and lower limb symmetry scores are the ratio of dominant limb tapping to non-dominant limb tapping, with a score closer to 1 indicating more symmetrical motor coordination between limbs.

Reliability of test measures in non-disabled participants

Methods

Fifteen non-disabled participants repeated the test battery within a week to examine the test-retest reliability of instrumented tapping tasks. Reliability assessments were calculated using Hopkins' reliability spreadsheet.[1] 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.[1]

Results

Reliability assessments indicated most test measures to be reliable in non-disabled participants (Table S3). Dominant lower limb tapping showed a decrease between repeated trials (-15±20 ms) although reliability assessments showed this test to have high absolute reliability (SEM = 14 ms, CV = 4.6 %) and reproducibility (ICC = 0.93). This test measure may prove to be more reliable if thorough familiarisation protocols are used prior to testing. Upper and lower limb symmetry scores showed lower ICC values (ICC = 0.42-0.54) than other test measures in non-disabled participants, although SEM (0.04) and CV (4.0-4.1 %) scores indicate these test measures might be more reliable in Para swimmers with brain injury that have larger variance in limb symmetry (Table S2).

Table S3. Reliability of instrumented tapping tasks in non-disabled participants.

	Trial 1 Mean (SD)	Trial 2 Mean (SD)	Δ T2 – T1 Mean (SD)	SEM	CV (%)	ICC (95% CI)
Bilateral upper limb tapping	100 (14)	103 (13)	3 (8)	5	5.4	0.85 (0.67-0.94)
Dominant upper limb tapping	185 (24)	182 (22)	-4 (11)	8	4.2	0.91 (0.78-0.96)
Non-dominant upper limb tapping	209 (27)	206 (23)	-3 (15)	11	5.2	0.85 (0.66-0.94)
Upper limb symmetry score	0.89 (0.04)	0.88 (0.05)	-0.01 (0.05)	0.04	4.1	0.42 (0.01-0.71)
Bilateral lower limb tapping	148 (27)	141 (23)	-5 (11)	8	5.4	0.93 (0.83-0.97)
Dominant lower limb tapping	281 (50)	266 (35)*	-15 (20)	14	4.6	0.93 (0.83-0.97)
Non-dominant upper limb tapping	301 (50)	291 (44)	-10 (22)	16	5.4	0.91 (0.78-0.96)
Lower limb symmetry score	0.93 (0.05)	0.92 (0.05)	-0.02 (0.05)	0.04	4.0	0.54 (0.15-0.79)

SEM = standard error of measurement, CV = coefficient of variation, ICC = intraclass correlation coefficient, CI = confidence interval. Indicates a significant change from trial 1 ($p < 0.05$).

Supplementary Material Appendix 3

Random forest classification of participants with and without brain injury

Methods

Random forest algorithm was used to establish the predictive validity of test measures in classifying participants with and without brain injury. Random forest is a non-linear machine learning technique that uses an ensemble learning method for classification and regression.[2] The 'randomForest' package in R was used for analysis.[2] Random forest included all test measures to predict participants with and without brain injury using an ensemble of 100 decision trees. The number of trees included in random forest was determined using random forest generalisation error that allows the out-of-bag (OOB) error convergence along the number of trees in the forest to be examined.[2]

The importance of predictor variables to classification was determined using the mean decrease in accuracy score calculated during the OOB error calculation.[2] The mean decrease in accuracy score describes the decrease in prediction accuracy in random forest that occurs when a single variable is excluded from the model. So, variables with larger mean decrease in accuracy scores are more important to prediction than other variables with lower scores. A feature selection method was also used to determine which variables could be excluded from random forest to improve the stability and parsimony of the model. The 'ggRandomForests' package was used to calculate the minimal depth and rank importance of predictor variables.[3] This involved calculating the distribution of *minimal depth* of variables and assumes variables with high impact on the prediction are those that most frequently split nodes nearest to the trunks of the trees. [4]

Results

The OOB error rate for the random forest was 3.92%. There were two Para swimmers with brain injury that were incorrectly classified as non-disabled participants. The ratio of votes assigned to participants' prior classification are shown in Figure S1. There were 33% and 35% of votes assigned to the prior classification of the Para swimmers that were incorrectly classified as non-disabled participants.

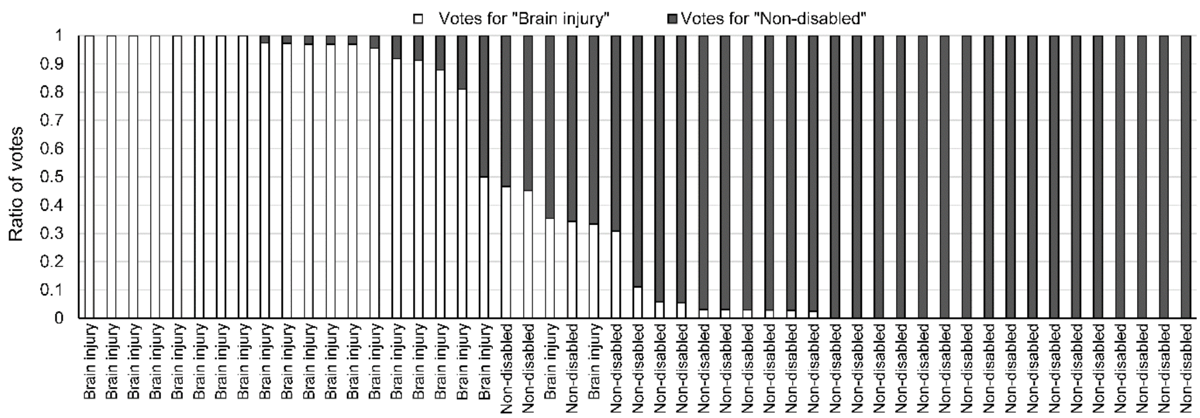


Figure S1. Ratio of votes to the classifications assigned by random forest algorithm. Ratio of votes (y) are shown for individual participants (x).

Variable importance scores are shown in Figure S2. Mean decrease in accuracy and minimal depth sores indicated non-dominant upper limb tapping, bilateral lower limb tapping, bilateral upper limb tapping and non-dominant lower limb tapping to be the most important variables in prediction of participants with and without brain injury. The variables showed equal rank of importance when examining the mean decrease in accuracy and minimal depth scores (Figure S3).

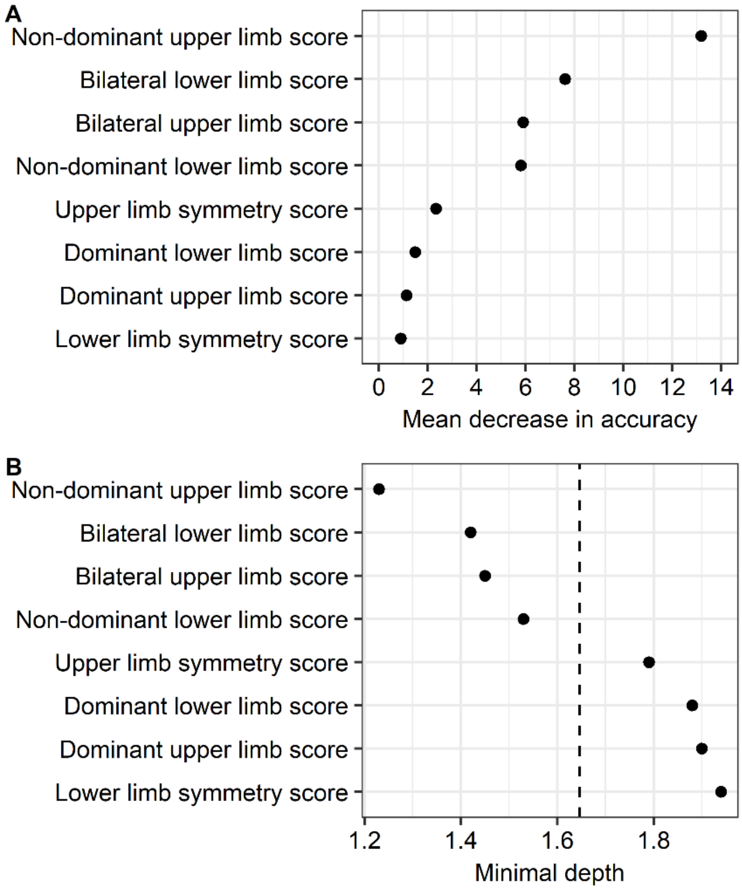


Figure S2. (A) Decrease in accuracy scores in rank order and (B) minimal depth scores in rank order showing the importance of test measures to prediction of participants with and without brain injury. The vertical dashed line in panel B indicates the maximal minimal depth for important variables.

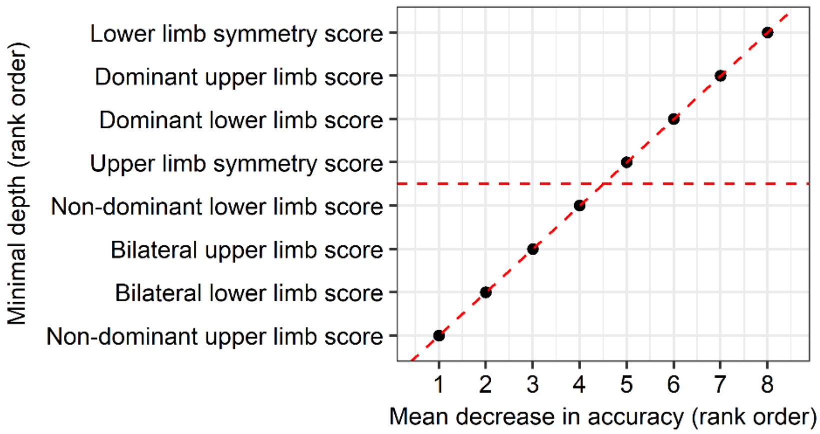


Figure S3. Comparison of minimal depth and mean decrease in accuracy rankings. This figure indicates variables had the same rank of importance for both methods of variable importance. The horizontal dashed line indicates the maximal minimal depth for important variables.

Supplementary Material Appendix 4

Partial least squares regression to predict maximal freestyle swim speed in Para swimmers with brain injury

Methods

The relationship between motor coordination impairment and maximal freestyle swim speed in Para swimmers with brain injury was established using ensemble partial least squares regression. The partial least squares method transforms the data to reduce both predictor and response variables to x- and y-components.[5] The derived x-components are then used to predict the response using regression analysis. The advantage of partial least squares regression is that while predictor variables may be colinear, the derived x-components will be independent of one another while also keeping most of the variance explained in the dataset. The method also has the advantage of being a dimension reduction technique, which has advantages when analysing datasets with many predictor variables or small sample sizes.

The 'enpls' package in R was used to conduct partial least squares regression on 100 Monte Carlo experiments with a sampling ratio of 0.8.[6] The ensemble learning method might improve the prediction accuracy and stability of partial least squares regression by exploiting the statistical distribution of variable coefficients and prediction errors. Motor coordination test measures that were found to have significant correlations ($p < 0.05$) with maximal freestyle swim speed were included in analysis - bilateral upper limb tapping was excluded. A maximum of 2 components were included in partial least squares regression and K-fold cross validation was used to examine the internal stability of the model.

A systematic approach was used for training, selecting important predictor variables, and improving the accuracy and stability of the model (Figure S4). This involved removing individual cases from analysis and step-wise removal of least important predictor variables. The vector of regression coefficients across multiple Monte Carlo experiments were used to indicate importance of predictor variables.[6] The variable importance score was calculated as the mean of the variable coefficient divided by the standard deviation of the variable coefficient. A larger importance score indicates are larger and more consistent regression coefficient. The entire participant cohort was included as a new test set in the optimised partial least squares regression model to establish the prediction accuracy and stability (Figure S5).

Results

The systematic approach used to improve the prediction accuracy and stability of the partial least squares regression model is shown in Figure S4. The first partial least squares regression included all participants and test measures that had a significant correlation with freestyle swim speed (Figure S4A). This model explained 72 % of the variance in maximal freestyle swim speed ($R^2 = 0.719$, RMSE = 0.185) although internal cross-validation indicated slight overfitting of the data ($cvR^2 = 0.646$, cvRMSE = 0.208). The three test measures related to lower limb tapping were unexpectedly found to be the most important predictors of maximal freestyle swim speed (Figure S4A). This could be explained by the inclusion of three participants with severe diplegic spasticity that were unable to complete the lower limb tapping tasks and were given a score reflecting one complete cycle for these test measures.

To determine the importance of predictor variables a second partial least squares regression was conducted only including participants that had completed all the included tapping tasks (Figure S4B). The importance of predictor variables ranked highest to lowest was dominant upper limb tapping, non-dominant upper limb tapping, bilateral lower limb tapping, non-dominant lower limb tapping, and dominant lower limb tapping. A step-wise removal of the least important predictor variable was done for a third (Figure S4C) and fourth (Figure S4D) partial least squares regression to improve the parsimony of the model. This resulted in improved prediction accuracy ($R^2 = 0.618$ vs. 0.605) and stability ($cvR^2 = 0.517$ vs. 0.465) of partial least squares regression.

The entire cohort of Para swimmers were included in a fifth partial least squares regression as a test set to derive predictions of the response using the regression coefficients from the optimised partial least squares (Figure S5). This model that included dominant upper limb tapping, non-dominant upper limb tapping, and bilateral lower limb tapping showed slight improvements in prediction accuracy and error ($R^2 = 0.724$, RMSE = 0.184) and stability ($cvR^2 = 0.675$, cvRMSE = 0.199) compared with the first partial least squares regression that included all test measures (Figure S4A).

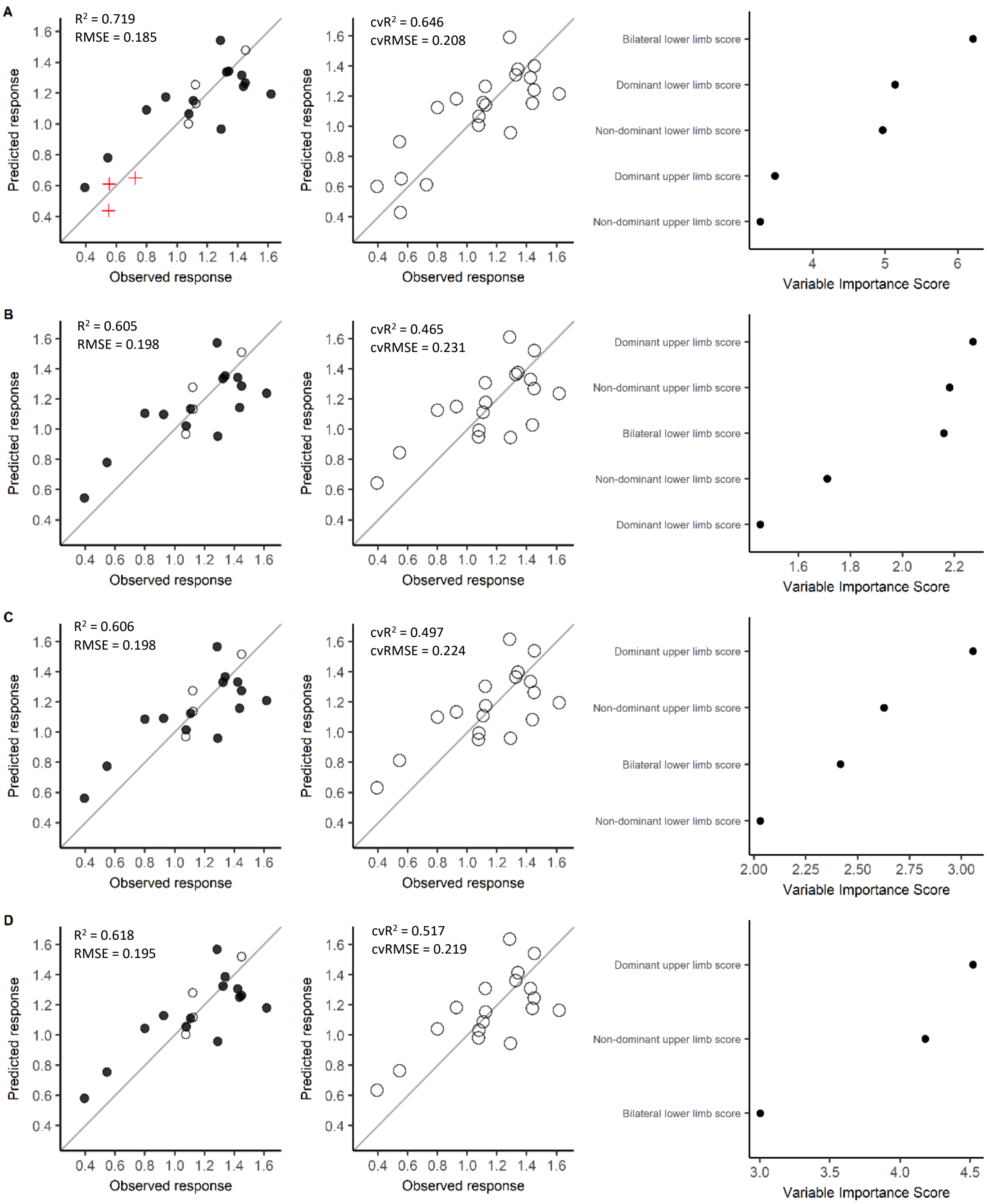


Figure S4. Prediction accuracy and error (left), internal cross-validation (middle), and variable importance scores (right) in partial least squares regressions. The accuracy and stability of the partial least squares regression was improved by removing individual cases (A) and variables with least importance (C and D) during model training.

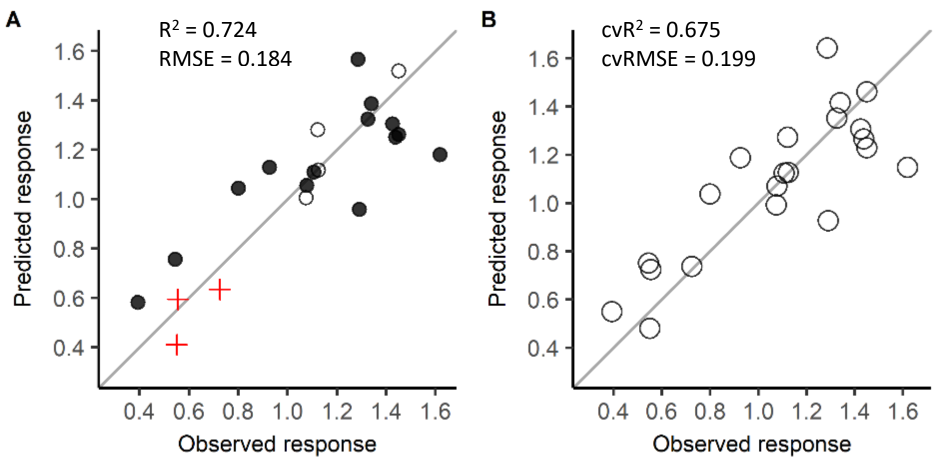


Figure S5. (A) Prediction and accuracy, and (B) internal cross validation of the optimised partial least squares regression that included dominant upper limb tapping, non-dominant upper limb tapping, and bilateral lower limb tapping as dependent variables.

Supplementary Material Appendix 5

References

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