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Improving the objectivity of the current World Para Swimming motor coordination test for swimmers with hypertonia, ataxia and athetosis using measures of movement smoothness, rhythm and accuracy

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ABSTRACT

The current protocol for classifying Para swimmers with hypertonia, ataxia and athetosis involves a physical assessment where the individual's ability to coordinate their limbs is scored by subjective clinical judgment. The lack of objective measurement renders the current test unsuitable for evidence-based classification. This study evaluated a revised version of the Para swimming assessment for motor coordination, incorporating practical, objective measures of movement smoothness, rhythm error and accuracy. Nineteen Para athletes with hypertonia and 19 non-disabled participants performed 30 s trials of bilateral alternating shoulder flexion-extension at 30 bpm and 120 bpm. Accelerometry was used to quantify movement smoothness; rhythm error and accuracy were obtained from video. Para athletes presented significantly less smooth movement and higher rhythm error than the non-disabled participants ($p < 0.05$). Random forest algorithm successfully classified 89% of participants with hypertonia during out-of-bag predictions. The most important predictors in classifying participants were movement smoothness at both movement speeds, and rhythm error at 120 bpm. Our results suggest objective measures of movement smoothness and rhythm error included in the current motor coordination test protocols can be used to infer impairment in Para swimmers with hypertonia. Further research is merited to establish the relationship of these measures with swimming performance.

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KEYWORDS
Para swimming; classification; movement smoothness; motor coordination

Introduction

The Paralympic Games are the major sporting event for athletes with physical impairments. As with all Para sports, Para swimming relies on a functional classification system to provide a robust framework for fair and equitable competition by minimising the impact that a competitor's impairment has on the outcome of their event (Tweedy & Vanlandewijck, 2011). In the current swimming classification system, swimmers with physical impairments are required to complete physical "bench tests" and a water-based technical assessment. The physical assessments are carried out by a medical classifier, typically a doctor or physiotherapist, and they include impairment specific medical assessments such as manual muscle testing for swimmers with a muscle power impairment, anthropometric measurement for swimmers with a limb deficiency, and motor coordination tests for swimmers with hypertonia, ataxia and athetosis (World Para Swimming, 2018). These assessments are used to establish the extent to which the individual's impairment limits their swimming performance and then to assign them to a sport class. There are ten sport classes for the freestyle, backstroke, butterfly and individual medley swim disciplines (e.g., S1-S10) and nine sport classes for the breaststroke swim discipline (SB1-SB9), with swimmers with the greatest activity limitation competing in the lower numbered sport classes (World Para Swimming, 2018). Para swimming combines athletes with different types of physical impairments. The impact of each athlete's impairment on swim performance, however, is estimated to be similar within each sport class. To ensure athletes are allocated to the correct class according to their activity limitation, and to guarantee that athletes within each class have equal chance to win irrespective of the type of impairment, it is essential the classification process is sport specific and training resistant, assessing valid measures of impairment which should be objective, ratio-scaled, reliable, precise, parsimonious and specific to the impairment of interest (Hogarth et al., 2019a; Tweedy & Vanlandewijck, 2011).

The current Para swimming classification system was developed using experts' opinion but with limited evidence-based methods. The manual muscle power and motor coordination assessments lack objective measures and standardisation, leaving room for subjectivity and personal interpretation of the testing protocol and testing outcome (Burkett et al., 2018; Tweedy & Vanlandewijck, 2011). The bench test to assess Para swimmers' motor coordination requires the medical classifier's subjective clinical judgment. Here the individual's ability to coordinate their limbs during alternating bilateral joint movements (e.g., flexion-extension of shoulder, elbow, wrist, fingers, hip, knee and ankle) at steady and increasing pace, through

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functional range of movement is observed (World Para Swimming, 2018). A score from 0 to 5 is given for each joint motion based on the judgment of the classifier.

Due to the lack of objective, reliable and precise measurement, the current physical assessment for motor coordination is not suitable for evidence-based classification. The reliance on subjective judgment compromises the achievement of inter- and intra-rater reliability and the ability to establish the impairment-performance relationship (Tweedy et al., 2014).

Motor coordination has been defined as the ability to move fluidly, rapidly and accurately (Connick et al., 2016). Individuals with hypertonia, ataxia and athetosis typically present more intermittent movement due to deficits in agonist and antagonist muscle synergy, a reduced ability to produce fast movement due to atypical force generation, and altered movement trajectory paths or limited range of movement compared with non-disabled individuals (Feng & Mak, 1997; Fernani et al., 2017; Van Thiel et al., 2000). These impairments are often described by type and severity, and the topographical distribution across the upper and lower limbs. Hypertonia, ataxia and athetosis are likely to affect swimming performance as an efficient technique requires rhythmic and coordinated limb movements (Seifert et al., 2004). Therefore, a valid classification test for motor coordination impairment in Para swimmers should incorporate measures of movement smoothness, accuracy and rhythm (temporal accuracy).

Movement smoothness represents spatio-temporal coordination and is often quantified using jerk data (Montes et al., 2014; Seifert et al., 2014) or by counting the number of peaks on a speed or acceleration curve (Cirstea & Levin, 2000; Leconte et al., 2016). A smooth movement is characterised as being single peaked; a higher number of peaks representing more changes in acceleration and therefore a less smooth movement (Balasubramanian et al., 2015). In an upper limb task, Cirstea and Levin (2000) reported that non-disabled participants presented a smooth and bell-shaped speed profile while participants with neurological disorders had multiple peaks. Ao, Song & Tong (2015) found the movement accuracy and smoothness of stroke patients performing elbow tracking tasks were inferior to those of non-disabled participants. They demonstrated that movement speed affected the participants' motor control strategy, and their movement smoothness, and was therefore an important consideration when designing tasks for clinical evaluation. This highlights the importance of standardising the task speed when evaluating motor coordination in Para swimmers with hypertonia, ataxia and athetosis; something that the current World Para Swimming test protocol fails to do.

Accuracy can be defined as the degree of approximation to a certain expected target (Hofer et al., 2005). Reaching a target requires from the nervous system a perception of the arm and the target, a movement plan and the execution of that plan (Liao & Kirsch, 2014). The final achievement (endpoint) variability depends on the noise within the nervous system and is found to increase at higher speeds. Noise in the triggering of the motor neurons can lead to deviation from the planned trajectory resulting in inaccuracy (Harris & Wolpert, 1998). Consequently, an increased movement variability can be observed in individuals with hypertonia, ataxia and athetosis (Cirstea & Levin, 2000). Studies have reported a poor timing ability and high movement variability in children with cerebral palsy (Johansson et al., 2014). Oliver et al. (2015) found that children with cerebral palsy presented less temporal accuracy than non-disabled children in pointing tasks at the end of a musical sequence. A metronome is commonly used to standardise the speed of participants' movements in order to evaluate rhythm (timing) error (Van Roon et al., 2005).

A recent study by Hogarth et al. (2019b) has attempted to address the limitations of the bench test for motor coordination. Their study examined the predictive and convergent validity of upper and lower limb instrumented tapping tasks to classify motor coordination impairments in Para swimmers. These tests involved participants tapping as rapidly and accurately as possible between tapping pads that recorded touches, allowing the time between consecutive touches to be calculated. Measures of mean movement time for repetitive upper limb tasks and lower limb tasks correctly classified 96% of participants with and without impairment and collectively explained up to 72% of the variance in freestyle swimming performance in Para swimmers. The authors concluded that instrumented tapping tests could thus improve objectivity and transparency in a revised Para swimming classification process. The study recorded the speed (frequency) and accuracy of limb movement; the smoothness of the movement and consistency of the movement speed (rhythm) were not considered. Given that elite swimmers swim more smoothly than non-elite swimmers (Ganzevles et al., 2019) and rhythm is an inherent feature of skilled swimming (Seifert et al., 2004), a test for motor coordination that includes a measure of movement smoothness and rhythm, in addition to accuracy measures, seems worthy of investigation.

The aim of this study was to improve the standardisation and objectivity of the current World Para Swimming physical assessment for swimmers with hypertonia, ataxia and athetosis by introducing practical, ratio-scaled measures of movement smoothness, rhythm, accuracy and endpoint variability to the testing protocol for motor coordination. It was hypothesised that: 1) Para athletes with hypertonia will achieve lower movement smoothness and accuracy, and higher rhythm error and endpoint variability, than non-disabled participants, and 2) Measures of movement smoothness, rhythm error, accuracy and endpoint variability can collectively discriminate between Para athletes with hypertonia and non-disabled participants.

Methods

Participants

Data were collected from 38 participants including non-disabled (n = 19) and Para athletes with the medical diagnosis of hypertonic cerebral palsy (n = 19) (Table 1). Para athletes from five different sport disciplines were recruited from the Irish and Czech Republic national and international squads. All Para athletes had previously gone through a national or international classification within their sport and training frequency varied from 3 to 7 sessions a week. All participants were free from musculoskeletal injury.

The lead author's university Ethics Committee approved the project and written informed consent was obtained from each

Table 1. Characteristics of Para athletes with hypertonia and non-disabled participants (mean (SD)).

	Para athletes with hypertonia (n = 19)	Non-disabled participants (n = 19)
Males	n = 14	n = 12
Females	n = 5	n = 7
Age (yrs)		
Males	26.6 (5.5)	24.8 (5.7)
Females	22.2 (6.1)	30.6 (3.9)
Body mass (kg)		
Males	72.9 (8.6)	75.2 (8.0)
Females	59.2 (8.6)	63.3 (9.6)
Height (m)		
Males	1.70 (0.10)	1.77 (0.04)
Females	1.59 (0.03)	1.63 (0.03)
Competitive standard	International (n = 13)	
	National (n = 6)	
Sport Para athletics	4	
Boccia	2	
Para cycling	2	
Football 7-a-side	1	
Para Swimming	10	
Swimming S class		
Males	S3 (n = 1)	
	S4 (n = 1)	
	S5 (n = 1)	
	S6 (n = 3)	
	S8 (n = 1)	
	S9 (n = 1)	
Females	S4 (n = 1)	
	S7 (n = 1)	
Topographical classification of the impairment	Quadriplegic (n = 6)	
	Hemiplegic (n = 6)	
	Diplegic (n = 7)	

participant prior to testing. The participants completed a questionnaire providing information regarding their impairment and sport. Height (m) and body mass (kg) were recorded. When the participant was unstable in the standing posture, or standing was not possible, height measurement was taken with them lying supine. Assessment of the participant's motor coordination components (smoothness, accuracy, rhythm, endpoint variability) was completed in a single testing session lasting approximately 50 minutes.

Experimental set-up

Participants were positioned in supine on a standard physiotherapy bed (182 cm × 62 cm). A GENEActiv tri-axial accelerometer (GENEActiv Action, Activinsights Ltd, Cambridgeshire, UK) was secured to the dorsal surface of both of the participant's wrists, midway between the radial and ulnar styloid processes. The accelerometer Y-axis was aligned with the long axis of the forearm and the X-axis created a perpendicular line across the distal radioulnar joint (GENEActiv instructions, 2012 version 1.2). Acceleration was sampled at 100 Hz. Before each testing session, the accelerometers' axes were statically calibrated using a horizontal surface as reference to ensure the vertical and horizontal axes outputs were −1 g and 0 g, respectively.

A physical target (Figure 1) consisting of two height-adjustable horizontal bars, each sub-divided into three 0.2 m foam sections, was constructed to provide feedback in relation to the movement path required. As joints are more susceptible to injury near their end-range of movement (Lugo et al., 2008) the target was positioned at 80% of the participant's maximal active shoulder flexion range of movement. This was assessed according to Norkin and White (2009) using a 360-degree goniometer with two 18 cm movable arms (CARCI Inc., Brazil).

A digital metronome (Shenzhen Meideal Musical Instruments Co., Ltd, China) was used to control the frequency

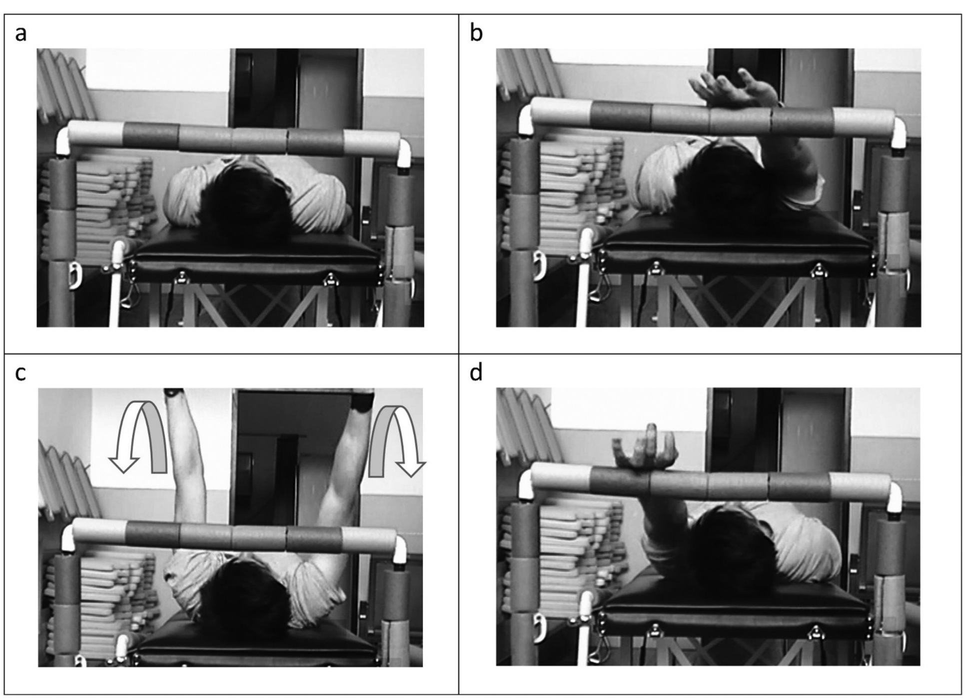

Figure 1. Phases of the movement task: (a) initial position; (b) end of right shoulder flexion/left shoulder extension; (c) mid-cycle position (left shoulder flexing, right shoulder extending); (d) end of left shoulder flexion/right shoulder extension.

and speed of the upper limb movements. Trials were recorded at 50 Hz with a camcorder (Sony HDR CX700, Sony Corporation, Japan) on a tripod located superior to the participant's head, positioned on the midline directed caudad 2 m from the plinth.

Test protocol and data collection

The joint movement assessed in this study was shoulder flexion-extension of the affected arm for Para athletes and non-dominant arm for non-disabled participants. Two 30 s trials of bilateral shoulder flexion-extension movements were performed with participants lying in supine with the lower limbs extended on the physio bed. As per the World Para Swimming testing protocol, right and left shoulder movements were performed alternately. Figure 1 illustrates the phases of the task required. Participants were instructed to alternately perform the flexion and extension of the shoulders in the vertical plane, keeping the palm of the hands facing down and the elbow extended at all times, touching the target with the back of the hand. As one hand touched the target, the opposite one simultaneously contacted the physio bed (Figure 1). Participants were asked to match the metronome rate by reaching the end of the flexion (physical target) and extension (physio bed) on the audible beat. They were asked to perform the movements smoothly and continuously with no pause when contacting the physical target or physio bed, and to contact the physical target in the same location on each movement cycle.

The test involved two trials in ascending speed which were separated by a 30 s rest period. The first trial, at 30 bpm, required the flexion and extension phases to each take 2.0 s; the second trial, at 120 bpm, required each phase to take 0.5 s. Standardised instructions were given before each trial and no verbal feedback was provided during the execution of the test. The participant did not perform a practice trial in advance of the task, movements were demonstrated by the researcher. To familiarise with the pace of the movement, the participant listened to the beat for 10 s and commenced the sequence of movement after a verbal command.

Data processing

From the 30 s of data recorded, the final 20 s were used for analysis. The first 10 s of each trial was considered a familiarisation phase during which the participant synchronised their limb movements with the metronome. Acceleration data were downloaded in coma-separated values file format and summarised into a signal magnitude vector, gravity-subtracted as described in earlier studies (Esliger et al., 2010), where the correction for gravity was undertaken to focus the outcome variable on dynamic rather than static accelerations ($1\ g = 9.81\ m{\cdot}s^{-2}$). Acceleration signals were filtered using a low pass Butterworth filter with a cut-off frequency of 8 Hz (Osu et al., 2011).

Each participant's movement smoothness was quantified by counting the total number of acceleration peaks occurring during the arm cycles over the final 20 s (Kamper et al., 2002; Leconte et al., 2016). An acceleration peak was defined as any local peak (maxima – minima) in the signal that was greater than a threshold value of 15% of the global peak (Kamper et al., 2002). This threshold was selected as higher thresholds (20%, 25% and 30%) failed to detect smaller relevant peaks from the data profile.

Rhythm error (timing) was assessed by computing the discrepancy between the expected timing and actual timing of the participant's arm movements at the end of the shoulder flexion and extension phases for each arm cycle. Timing differences were obtained to the nearest 0.02 s from the video recordings (Kinovea 0.7.10, www.kinovea.org). The absolute timing errors for each cycle were summed and then a mean value computed for the arm cycles performed in the last 20 s. Higher rhythm error values represent poorer synchronisation of movement with the metronome.

To quantify movement accuracy, the contact position on the physical target was recorded for each movement cycle. Each foam section of the target was subsequently divided into 2 equal parts using Kinovea to provide six 10 cm zones for each arm. Participants were instructed to contact the same zone on the target for all arm cycles; the zone touched in the first cycle was used as a reference. Accuracy was assessed by recording the zone contacted by the hand (middle finger) on each subsequent cycle and comparing this to the reference zone. Accuracy was defined as the mean absolute distance (in zones) from the reference zone, contacted by the hand. Thus, an accuracy score of 1.0 would indicate that the participant had missed the reference zone by, on average, 1 zone in the trial. The variability in the participants' hand contact location, hereafter referred to as endpoint variability, was defined as the root mean square difference of each cycle score (zone number) relative to the mean cycle score.

Statistical analysis

Statistical tests were conducted using R version 3.6.2 (R Core Team, 2019). The Levene's test and Shapiro-Wilk test showed unequal variances between groups and non-normality of distribution of data. Therefore, differences in the number of peaks, rhythm error, accuracy and endpoint variability between the non-disabled and Para athlete groups at 30 bpm and 120 bpm were analysed with Mann–Whitney U tests. Separate Wilcoxon signed-rank tests were conducted to determine if non-disabled and Para athlete groups showed differences in outcomes measures between tests at 30 bpm and 120 bpm. Estimates are reported with 95% confidence intervals and an alpha value of 0.05 was used to indicate statistical significance. Cliff's Delta (*d*), a non-parametric measure of effect size, was also calculated with 95% confidence intervals and interpreted as negligible (≤0.147), small (≤0.33), medium (≤0.477) and large (>0.477) (Romano et al., 2006).

Random forest algorithm was used to establish the predictive validity of variables to classify Para athletes and non-disabled participants. Random forest uses a bagging and bootstrapping technique to construct multiple decisions trees. A bootstrapping sample is derived from approximately two-thirds of the data and used to train a decision tree; the remaining one-third of the data are used to test the decision tree and calculate the out-of-bag error rate. Receiver operating characteristics curve was used to summarise the sensitivity and specificity of the trained random forest model using the ratio of votes assigned for each case for 100 decision trees. The area under the receiver operating characteristics curve (AUC) was calculated to summarise the accuracy of the model. The AUC ranges between 0 and 1 with a value of 0.5 and 1.0 inferring a 50% and 100% probability that a random case will be correctly classified by the model, respectively. The importance of predictor variables was determined using the mean decrease in accuracy score, which indicates the decrease in prediction accuracy that occurs when a single variable is excluded during the out-of-bag error calculation.

Results

Movement smoothness

Figure 2 presents wrist acceleration profiles for a non-disabled participant, and for participants with diplegia, hemiplegia and quadriplegia, for a typical single flexion-extension cycle performed at 30 bpm and 120 bpm. At 30 bpm, all four participants reached the physical target close to 50% of the movement cycle, indicating that the shoulder flexion and extension phases were performed in equal duration. However, at 120 bpm only the non-disabled participant reached the physical target close

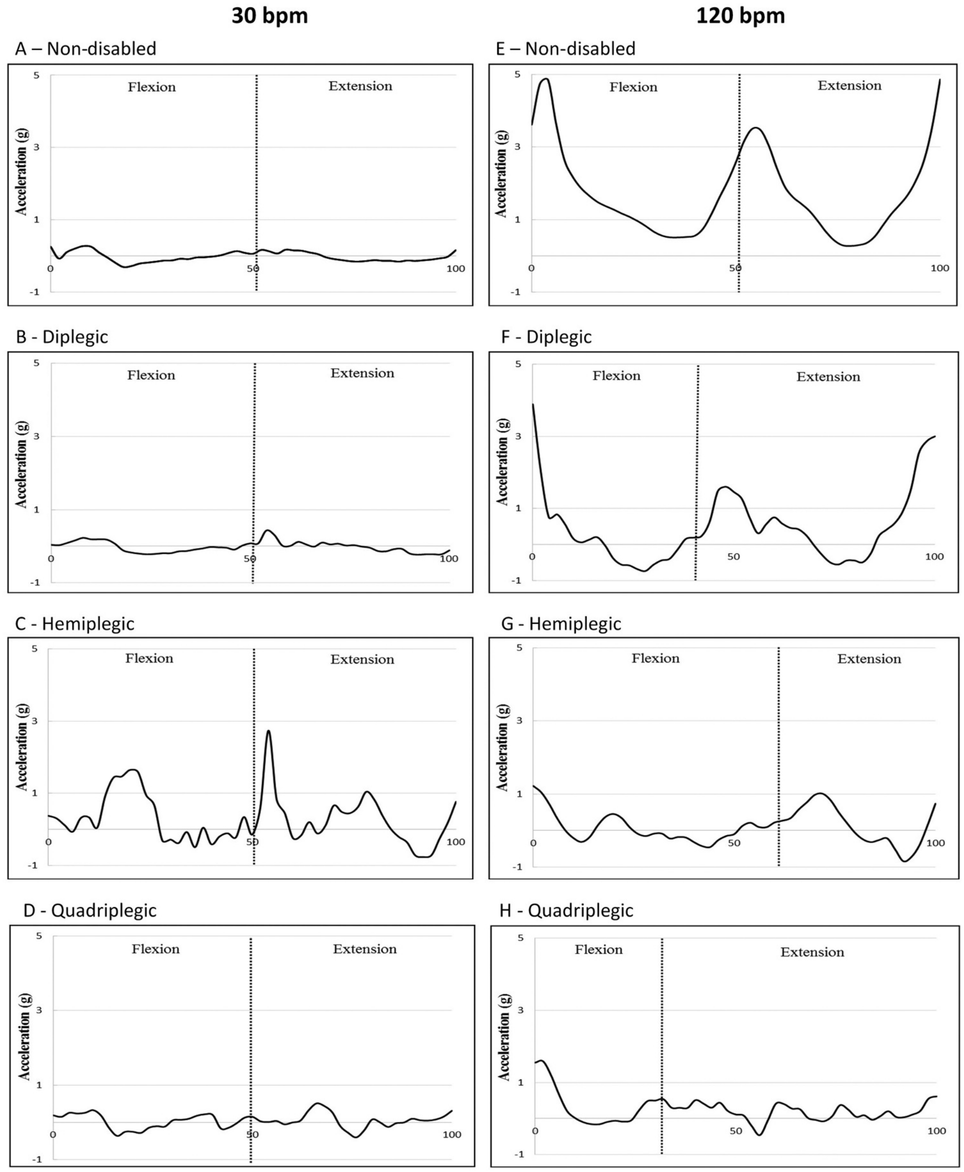

Figure 2. Wrist acceleration profiles from one shoulder flexion-extension cycle of four representative participants: Non-disabled (panels A and E), diplegic (panels B and F), hemiplegic (panels C and G), and quadriplegic (panels D and H). Left and right side panels present data for the 30 bpm and 120 bpm trials, respectively. Vertical line denotes instant of hand contact with physical target.

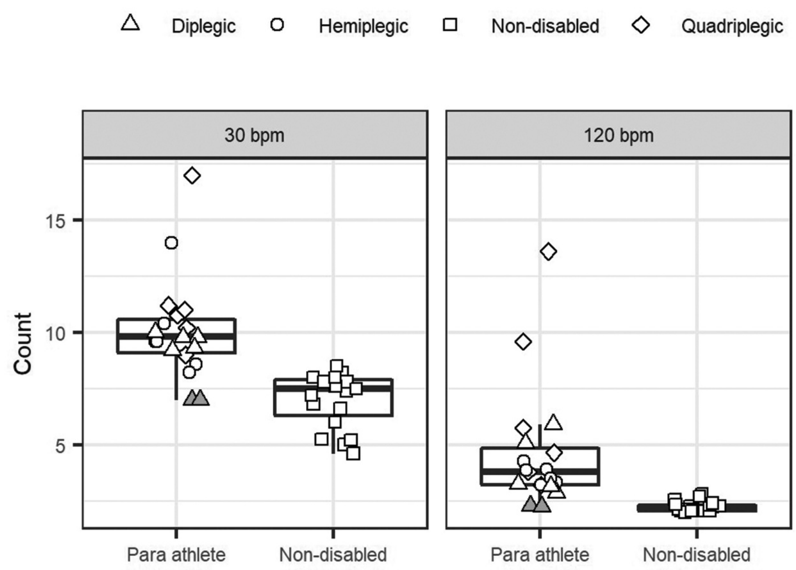

Figure 3. The number of acceleration peaks during cyclic upper limb actions performed at 30 bpm and 120 bpm in non-disabled participants and Para athletes. The grey symbols represent participants that were incorrectly classified during out-of-bag predictions during random forest modelling.

to 50% of the cycle. The participants with hypertonia were unable to maintain the required movement frequency and the shoulder flexion and extension phases were not performed in equal proportion.

Boxplots for the movement smoothness (No. acceleration peaks) of the Para athlete and non-disabled groups are presented in Figure 3. Para athletes reported a significantly higher number of peaks than non-disabled participants during cyclic upper limb movements at 30 bpm (2.6 [1.8, 3.6], U = 25.5, $p < 0.001$, $d = 0.86$ [0.55, 0.96]) and 120 bpm (1.45 [1.1, 2.2], U = 16, $p < 0.001$, $d = 0.91$ [0.10, 0.99]); this result supports the experimental hypothesis that Para athletes would record a higher number of acceleration peaks than non-disabled participants. Both Para athletes (–5.8 [–4.9, –6.7], V = 187, $p < 0.001$, $d = -0.86$ [–0.56, –0.96]) and non-disabled participants (–4.9 [–6.1, –5.6], V = 190, $p < 0.001$, $d = -1.0$ [–0.99, –1.0]) recorded fewer peaks during arm cycles performed at 120 bpm than at 30 bpm.

Rhythm error (timing)

Boxplots for the rhythm error of the two groups are presented in Figure 4. Para athletes reported a higher rhythm error than non-disabled participants during cyclic upper limb movements at 30 bpm (0.16 s [0.04, 0.27 s], U = 89, $p = 0.008$, $d = 0.51$ [0.13, 0.76]) and 120 bpm (0.53 s [0.26, 0.80 s], U = 53.5, $p < 0.001$, $d = 0.7$ [0.2, 0.91]); this result supports the experimental hypothesis that Para athletes would have higher rhythm error than non-disabled participants. Non-disabled participants reported a small decrease in rhythm error at 120 bpm

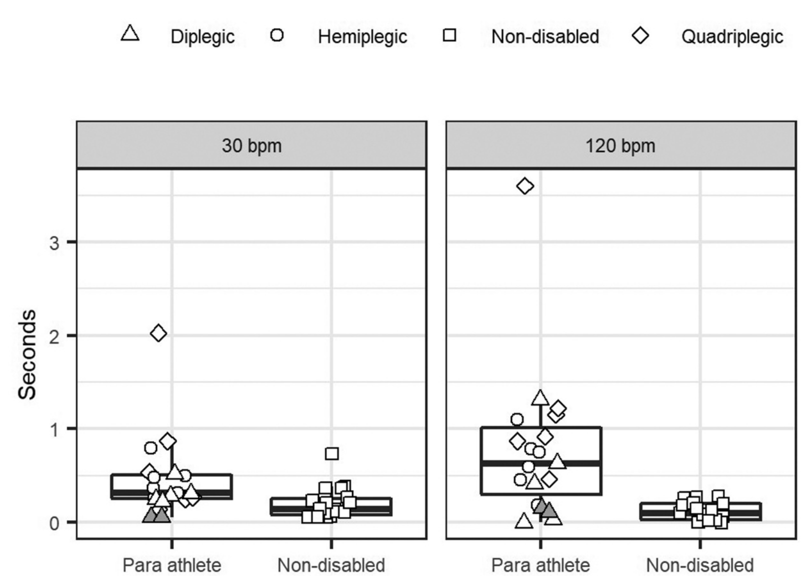

Figure 4. The rhythm error during cyclic upper limb actions performed at 30 bpm and 120 bpm tempos in non-disabled participants and Para athletes. The grey symbols represent participants that were incorrectly classified during out-of-bag predictions during random forest modelling.

compared to 30 bpm (−0.07 s [0.02, −0.16 s], V = 135, p = 0.11, *d* = −0.31 [−0.61, 0.06]), although Para athletes showed higher rhythm error with increasing tempo (0.35 s [0.04, 0.60 s], V = 41, p = 0.028, *d* = 0.30 [−0.1, 0.61]).

Accuracy and endpoint variability

Boxplots showing the accuracy and endpoint variability scores of the two groups are presented in Figure 5. There were no significant differences in absolute accuracy between Para athletes and non-disabled participants at 30 bpm (0.25 [0, 0.55], U = 109.5, p = 0.06, *d* = 0.36 [−0.02, 0.65]) or at 120 bpm (0.14 [−0.1, 0.46], U = 113.5, p = 0.13, *d* = 0.30 [−0.1, 0.61]) (Figure 5 (a)); this finding does not support the experimental hypothesis that Para athletes would have lower absolute accuracy than non-disabled participants. Para athletes and non-disabled participants also recorded similar accuracy scores at 30 bpm and 120 bpm (PA: 0.16 [−0.14, 0.46], V = 53, p = 0.28, *d* = 0.19 [−0.21, 0.53]; ND: 0.17 [−0.11, 0.42], V = 63, p = 0.21, *d* = 0.3 [−0.08, 0.61]). There was also no significant difference in the endpoint variability between Para athletes and non-disabled participants at 30 bpm (0.09 [0, 0.30], U = 110, p = 0.06, *d* = 0.36 [−0.02, 0.65]). However, Para athletes had higher endpoint variability at 120 bpm than non-disabled participants (0.14 [0.01, 0.30],

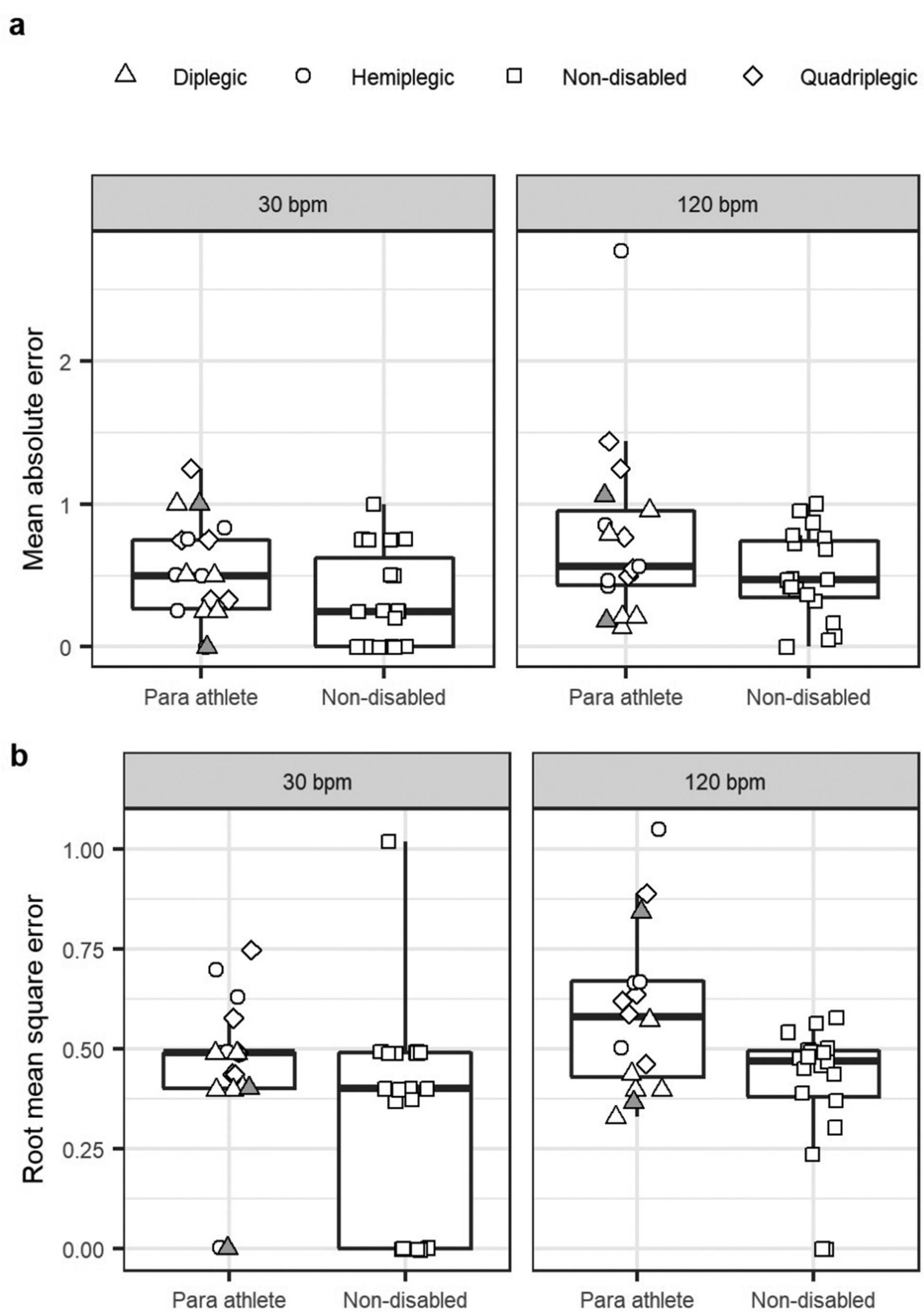

Figure 5. The accuracy error (a) and endpoint variability in target contacts (b) during cyclic upper limb actions performed at 30 bpm and 120 bpm in non-disabled participants and Para athletes. The grey symbols represent participants that were incorrectly classified during out-of-bag predictions during random forest modelling.

U = 83.5, p = 0.02, d = 0.45 [0.06, 0.72]); the result at higher speed supports the experimental hypothesis that Para athletes would have higher endpoint variability that non-disabled participants, the result at the lower speed does not. Further, non-disabled participants showed similar variability in the zone contacted between 30 bpm and 120 bpm (0.08 [−0.09, 0.27], V = 58, p = 0.24, d = 0.25 [−0.13, 0.56]) while Para athletes showed higher variability with the increase in tempo (0.12 [0.01, 0.25], V = 24, p = 0.04, d = 0.30 [−0.12, 0.63]).

The out-of-bag error rate for the random forest model was 5.26%, with the model successfully classifying 17/19 (89%) of Para athletes and 19/19 (100%) of the non-disabled participants during out-of-bag predictions (Figure 6(a), AUC = 0.924). The three most important variables to model accuracy were the number of acceleration peaks at 30 and 120 bpm, and rhythm error at 120 bpm (Figure 6(b)). The predictor variables including absolute accuracy at 30 and 120 bpm, and endpoint variability at 30 bpm had mean decrease in accuracy scores close to zero showing that there were no considerable decreases in model accuracy when these variables were removed during out-of-bag error calculation (i.e. they are redundant and could be removed from the model). Partial dependence plots show the probability of participants being classified as Para athletes based on scores for the three most important predictor variables, acceleration peaks at 30 bpm (Figure 6(c)), acceleration peaks at 120 bpm (Figure 6(d)) and rhythm error at 120 bpm (Figure 6(e)).

Discussion

Developing valid tests of motor coordination for Para swimmers with hypertonia, ataxia and athetosis is a challenging yet essential stage in the development of an evidence-based classification system for this group of athletes. This study aimed to improve the standardisation and objectivity of the current World Para Swimming physical assessment for swimmers with hypertonia, ataxia and athetosis by introducing practical, ratio-scaled measures of movement smoothness, rhythm and accuracy to the testing protocol for motor coordination.

We found that Para athletes with hypertonia exhibited significantly lower movement smoothness and higher rhythm error than non-disabled participants when performing a bilateral alternating shoulder flexion-extension task at 30 and 120 bpm. Para athletes also displayed higher endpoint variability than the non-disabled group at the higher test speed. There was no significant difference in accuracy between the two groups at either speed.

The test measures selected for this study were able to distinguish between those with and without hypertonia. Random forest algorithm successfully classified 89% of Para

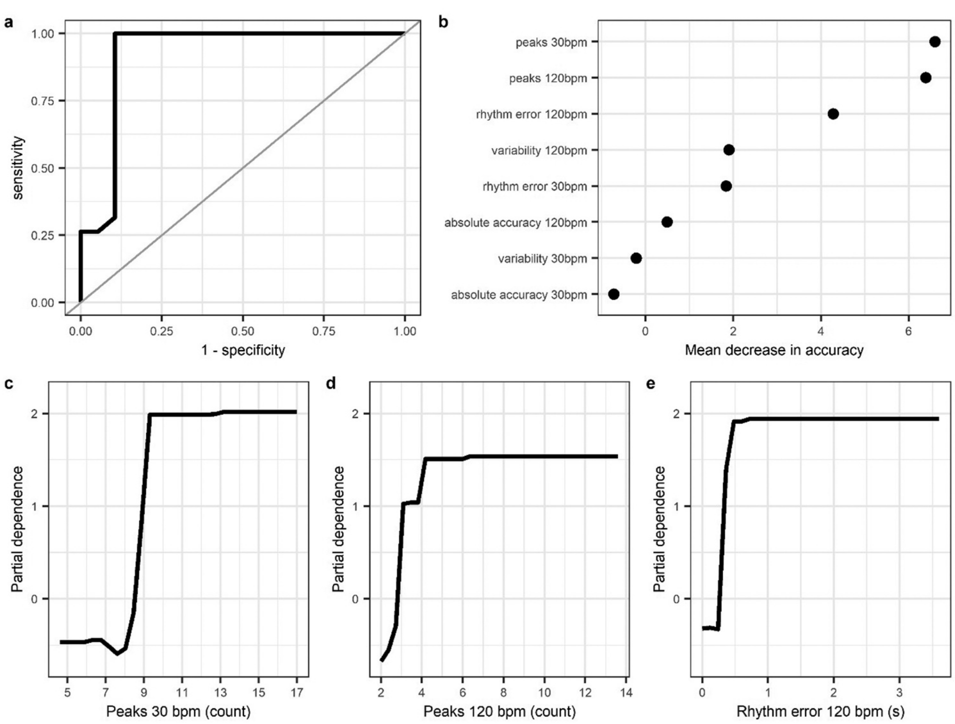

Figure 6. Accuracy and variable importance of the random forest model in classifying Para athletes and non-disabled participants. (a) The receiver operating characteristics (ROC) curve shows the accuracy of the random forest model in classifying Para athletes and non-disabled participants (AUC = 0.924). (b) Mean decrease in accuracy scores are used to indicate the importance of variables in classifying Para athletes and non-disabled participants. A higher mean decrease in accuracy score for a given variable indicates a greater reduction in classification accuracy when this variable is singularly removed from the model, and therefore a greater importance in correctly classifying cases. Partial dependence plots were used to interpret the marginal effect of the three most important variables, (c) acceleration peaks at 30 bpm, (d) acceleration peaks at 120 bpm, and (e) rhythm error at 120 bpm, in predicting whether a case is a Para athlete or non-disabled participant. Partial dependence values above 0 indicate a positive influence for classification in the model. For example, when considering the effect of acceleration peaks at 30 bpm (c) there is greater chance that participants will be classified as Para athletes if they achieve a count of 9 or more acceleration peaks.

athletes and 100% of the non-disabled participants, with the three most important predictor variables being movement smoothness at 30 and 120 bpm, and rhythm error at 120 bpm. Two Para athletes were incorrectly classified as non-disabled participants. It is noteworthy that the two most important variables for classifying participants with and without motor coordination impairment in this study, movement smoothness and rhythm error, are two aspects of motor coordination not measured by the instrumented tapping tests that have previously been proposed (Connick et al., 2016; Hogarth et al., 2019b).

The poorer movement smoothness (higher No. of acceleration peaks) exhibited by the Para athletes compared to the non-disabled participants in the current study is consistent with the findings of many previous studies (e.g., Ao et al., 2015; Leconte et al., 2016; Rohrer et al., 2002). The presence of a high number of peaks may relate to a lack of coordination between agonist and antagonist muscles and the difficulty in regulating multi-joints interaction torque (Artilheiro et al., 2014; Goldvasser et al., 2001). It may also reflect the triggering of spasticity or increased tonic stretch reflexes (Laczko et al., 2017).

Both groups in this study produced significantly smoother movement when performing the task at the higher test speed. This finding is supported by previous studies demonstrating that movement speed influences participants' motor control strategy and their movement smoothness (Ao, Song & Tong, 2015; Vikne et al., 2013). The inter-relationship between movement speed and movement smoothness highlights the importance of standardising the task speed when evaluating motor coordination in Para swimmers with hypertonia, ataxia and athetosis but also indicates that more than one task speed should be used.

Although instructed to perform a continuous, cyclic movement in time with the metronome, most of the Para athletes were observed executing the task in an episodic manner, presenting some delay in starting the reverse shoulder movement after reaching the target; this is likely due to the impairment in motor processing and deficit in the efferent mechanism (Chae et al., 2001). This non-continuous movement impacted the movement rhythm of the Para athlete group, significantly increasing their mean rhythm error compared to the non-disabled group. In addition to the observed pause at the end of each cycle, it was also noted that the participants with hypertonia tended to complete fewer arm cycles than the non-disabled group in the 30 s trials, at both test speeds. The non-disabled group achieved similar rhythm error scores at both test speeds. In contrast, the Para athletes' rhythm error was significantly higher at 120 bpm than at 30 bpm. This finding again emphasises the importance of selecting task speeds that best expose the impairment under scrutiny and that different test speeds are likely required to assess the separate components of motor coordination. The current World Para Swimming testing protocol involves the medical classifier giving a verbal command to the Para swimmers to start the movement slowly, increasing its speed as required. However, that protocol has been shown to lack standardisation and therefore athletes are submitted to different testing conditions depending on the classifier. The use of a metronome was found to be a practical method of standardising movement speed (tempo) to allow rhythm error to be quantified and for a confounding variable to be controlled.

Even though the Para athletes in the current study presented less smooth movement and higher rhythm errors than the non-disabled group, they were not significantly different from that group in the accuracy of their hand contacts at the end of each shoulder flexion cycle. This finding opposes previous research that has shown the lack of neural feedback control of individuals with neurological disorders results in decreased accuracy when executing a movement (Alberts et al., 2000; Chang et al., 2005; Cirstea & Levin, 2000). One possible explanation for this unexpected result could be related to the longer time taken by the Para athletes to perform each arm cycle, as they lagged behind the metronome. This might suggest that Para athletes achieved comparable accuracy to non-disabled participants by altering their movement speed resulting in poorer movement smoothness and rhythm error. It is noteworthy that absolute accuracy scores at both speeds, and the endpoint variability at the slower speed, were the least important predictor variables in the random forest algorithm and could be excluded from the model with minimal effect on model accuracy. However, the physical target used in this study was found to be a useful instrument to guide Para athletes regarding the movement pathway required to encourage movement accuracy. The inclusion of accuracy and endpoint variability assessments in the World Para Swimming motor coordination test protocols might be important to obtain valid and reliable measures of movement smoothness and rhythm error, despite not being important to infer impairment in Para athletes with hypertonia. Further research is warranted to clarify the importance of accuracy and endpoint variability in the assessment of coordination for the purpose of classification in Para swimming.

Supporting the predictive ability of the objective measures assessed in this study in classifying individuals with and without hypertonia, the random forest algorithm had a 95% success rate during out-of-bag predictions. The partial dependence plots for the three most important predictor variables, acceleration peaks at both speeds and rhythm error at 120 bpm, show the test scores associated with a steep increase in probability of being classified with hypertonia may be used to guide minimum impairment criteria (Figure 6(c-e)). It is important that the minimum impairment criteria are also guided by the relationship between these variables and activity limitation in swimming. However, it is appropriate that the established minimum impairment criteria are greater or equal to the minimum level of impairment that can be detected with these measures.

Two Para swimmers were incorrectly classified as non-disabled participants. As both individuals had diplegic cerebral palsy and were primarily affected in their lower limbs, it was not unexpected that they achieved similar results to non-disabled participants in the upper limb assessment. This highlights the importance of assessing both upper and lower limb motor coordination, and trunk control to build a complete profile of an athlete's motor coordination impairment. The measurement protocols presented in this paper could be applied to the evaluation of the lower limb and, potentially modified to assess trunk function. This study has focussed on improving the objectivity of a coordination test used currently for classifying Para swimmers. It seems likely that the measures of movement smoothness and rhythm error implemented in this study could be beneficial for classification in other Para sports, particularly those involving cyclic, repetitive limb movements such as Para rowing, Para athletics (track) and Para cycling.

Limitations of the study

Although this research aimed to improve the current World Para Swimming test protocol for classifying Para swimmers with hypertonia, athetosis and ataxia, all the participants coincidently had the medical diagnosis of hypertonic cerebral palsy. Further research with a larger cohort of Para athletes, including those with athetosis and ataxia is thus required. As participants for this study were drawn from a range of Para sports it was not possible to explore the relationship between the test scores and swimming performance. Further work is therefore required to fully understand the impairment-performance relationship using these objective measures of movement smoothness and rhythm error.

Conclusion

The current World Para Swimming protocol for assessing swimmers with hypertonia, ataxia and athetosis lacks objective, reliable and precise measurements, making it unsuitable for evidence-based classification. This study introduced measures of movement smoothness, rhythm, accuracy and endpoint variability to one of the tests, an alternating bilateral shoulder flexion-extension task, to enable the objective assessment of motor coordination impairment in Para athletes with hypertonia. A random forest model identified movement smoothness and rhythm (timing) error as the two most important variables for discriminating between non-disabled participants and those with hypertonia. These key variables were significantly influenced by the task speed used. This highlights the need to standardise the test speed when evaluating Para swimmers and to employ more than one speed during the process.

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No potential conflict of interest was reported by the author(s).

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