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Active Drag as a Criterion for Evidence-based Classification in Para Swimming

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ABSTRACT

PAYTON, C., L. HOGARTH, B. BURKETT, P. VAN DE VLIET, S. LEWIS, and Y. OH. Active Drag as a Criterion for Evidence-based Classification in Para Swimming. *Med. Sci. Sports Exerc.*, Vol. 52, No. 7, pp. 1576–1584, 2020. **Introduction:** Paralympic classification should provide athletes with an equitable starting point for competition by minimizing the impact their impairment has on the outcome of the event. As swimming is an event conducted in water, the ability to overcome drag (active and passive) is an important performance determinant. It is plausible that the ability to do this is affected by the type and severity of the physical impairment, but the current World Para Swimming classification system does not objectively account for this component. The aim of this study was to quantify active and passive drag in Para swimmers and evaluate the strength of association between these measures and type of physical impairment, swimming performance, and sport class. **Methods:** Seventy-two highly trained Para swimmers from sport classes S1 to S10 and 14 highly trained nondisabled swimmers were towed by a motorized winch while the towing force was recorded. Passive drag was measured with the arms held by the side; active drag was determined during freestyle swimming using an assisted towing method. **Results:** Active and passive drag were higher in Para swimmers with central motor and neuromuscular impairments than for nondisabled swimmers and were associated with severity of swim-specific impairment (sport class) and maximal freestyle performance in these swimmers ($r = -0.40$ to -0.50, $P \leq 0.02$). Para swimmers with anthropometric impairments showed similar active and passive drag to nondisabled swimmers, and between swimmers from different sport classes. **Conclusions:** Para swimmers with central motor and neuromuscular impairments are predisposed to high active drag during freestyle swimming that impacts on their performance. It is recommended that drag measures be considered in revised classification for these swimmers, but not for those with anthropometric impairments. **Key Words:** PARALYMPICS, IMPAIRMENT, WATER-TEST, TOWING, FREESTYLE, DRAG RATIO

The International Paralympic Committee (IPC) is the global governing body of the Paralympic movement and acts as the international federation for 10 Para sports including Para swimming. One of its key roles is to provide a classification system for each of these 10 sports. An effective classification system is intended to provide athletes with an equitable starting point for competition by minimizing the impact that their impairment has on the outcome of the event (1). In the current swimming classification system, physically impaired swimmers undergo both a medical and technical assessment, the purpose of which is to evaluate the extent to which their impairment limits their swimming performance (2). They are then assigned to a sport class ranging from 1 (most severe activity limitation) to 10 (least activity limitation). Swimmers currently eligible to compete in Para swimming events are those with anthropometric impairments, including swimmers with a short stature, limb deficiency or a restricted range of movement, and those with central motor and neuromuscular impairments. This latter group comprises a wide range of physical impairments including hypertonia, ataxia, athetosis, and impaired muscle power due to medical conditions, such as cerebral palsy and spinal cord injury.

A swimmer's speed depends on their capacity to produce propulsion effectively while minimizing the drag forces from the water (3). Although the factors that affect propulsion are considered in detail under the present classification system, very limited allowance is made for differences in hydrodynamic drag due to physical impairment. However, World Para

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Swimming, the international federation for the sport, recently announced a review of the current Functional Classification System (4), with drag to be one of the factors considered as part of that process. Therefore, studies that evaluate the strength of association between drag and swimming performance in Para swimmers are required.

Drag can be evaluated under two conditions: passive drag is the resistance the swimmer produces when moving through the water while holding a fixed body position; active drag is the resistance produced when performing a swimming stroke. Oh et al. (5) recently reported a strong negative correlation between Para swimmers' passive drag (normalized for body mass [BM]) and their sport class (Kendall's tau (τ) = −0.60), that is, more severe swimming-specific impairments were associated with higher passive drag.

Research into active drag has focused almost exclusively on the front crawl stroke. This may be due to it being the fastest of the four competitive strokes. Additionally, as it has a more constant intracyclic speed than the other strokes, it is the best-suited to several of the popular methods for estimating active drag, which are underpinned by the assumption of constant swimming speed (6). Although there have been numerous studies of active drag in nondisabled swimmers over the past four decades (e.g., 7,8,9), to the best of the authors' knowledge, only one study of active drag in physically impaired swimmers has been undertaken, and this was limited to a single participant (10).

Active drag is an important determinant of performance in nondisabled swimmers (3), and it is highly influenced by the swimmer's technique (11,12,13,14). In nondisabled swimmers, active drag has often been viewed as a measure of "skill" because swimmers who perform arm strokes and leg kicks while causing minimal disturbance to the water are considered to have a better "technique" than those whose movements cause more disturbance. It has also been suggested that the ratio of passive to active drag, termed the thrust deduction (15), or the reciprocal of this, called the technique drag index (12) may provide a useful measure of the swimmer's effectiveness in producing propulsion. If two swimmers with similar active drag are compared at the same speed, the one with the higher thrust deduction is more effective as they have created less of an increase in drag with their propulsive actions. However, the validity of this notion for swimmers with physical impairments has not been investigated, and active drag may also reflect factors, such as strength, range of motion, and coordination, which vary considerably between Para swimmers, depending on the nature of their impairment.

There is currently no empirical evidence to support or reject the notion of using active drag data to help classify swimmers with physical impairment. Research that assesses the strength of association between type and severity of impairment and key determinants of performance is essential for the development of evidence-based classification systems for Para sports (16). Thus, a comprehensive study of how type and severity of physical impairment affect active drag and its relationship with swimming performance is required to evaluate whether active drag is a suitable criterion for classification in Para swimming. Active drag measurement might provide a valid assessment of activity limitation in Para swimming classification if it is found to be impacted on by type and severity of physical impairment, and increases in active drag resulting from physical impairment are associated with decreases in swimming performance.

The aim of this study was to quantify active and passive drag measures in Para swimmers and evaluate the strength of association between these measures and type of physical impairment, swimming performance, and sport class. A secondary aim was to establish whether type of physical impairment influences the relationships between drag measures, severity of impairment, and maximal freestyle swimming performance.

It was hypothesized that: 1) Para swimmers with physical impairments would have higher active and passive drag measures than nondisabled swimmers, 2) Para swimmers' active and passive drag measures would have a significant association with their sport class, 3) the ratio of passive to active drag would be positively related to sports class, and 4) active and passive drag measures would be associated with maximal freestyle swimming performance in Para swimmers with physical impairment. It was expected that certain types of physical impairment would be more predisposed to creating high drag forces that impact on their freestyle swimming performance.

METHODS

Participants

Seventy-two (72) highly trained Para swimmers (43 men and 29 women) from sport classes S1 to S10 participated in this study. A cohort (n = 14) of highly trained nondisabled swimmers was also included. The Para swimmer group comprised 36 with anthropometric impairments and 36 with central motor and neuromuscular impairments. Participants' characteristics are shown in Table 1. An *a priori* G*power analysis indicated that this study required a minimum of 23 participants in each group to have 80% power for detecting a medium-sized effect when using a 0.05 criterion for statistical significance.

Testing procedures were approved by the lead author's faculty ethics committee, and all swimmers provided written informed consent before participating. Throughout this study, "sport class" refers to the swimmer's S classification as swimmers were tested using the technique they use in a freestyle (S) event. In most cases, this was the front crawl technique but for four swimmers, front crawl was not possible due to the type and severity of their impairment (Table 1). These swimmers completed all tests in the supine position.

Experimental Setup

Data were collected in 25- and 50-m swimming pools with a minimum depth of 1.8 m and water temperatures typically around 27°C. The participants' maximal swimming speed (v_{MAX}) through a 10-m calibrated test zone was determined

TABLE 1. Characteristics of nondisabled swimmers and para swimmers with physical impairments.

		Central Motor and Neuromuscular	Anthropometric	Nondisabled
	Males (n = 47)	n = 25	n = 18	n = 4
	Females (n = 39)	n = 11	n = 18	n = 10
Age (yr)	Males	27.3 (7.6)	20.1 (3.8)	22.0 (2.7)
	Females	26.7 (10.0)	20.6 (5.7)	19.2 (2.7)
BM (kg)	Males	67.8 (10.1)	64.3 (10.8)	81.3 (7.2)
	Females	55.6 (7.3)	54.7 (5.1)	63.1 (3.9)
Stature (cm)	Males	170.7 (9.0)	163.2 (20.2)	188.4 (7.1)
	Females	156.5 (8.3)	155.1 (20.9)	171.5 (4.5)
Sport class		S1 (n = 1)[a]	S5 (n = 3)	
		S3 (n = 3)[a]	S6 (n = 4)	
		S4 (n = 4)	S7 (n = 4)	
		S5 (n = 5)[a]	S8 (n = 8)	
		S6 (n = 6)	S9 (n = 14)	
		S7 (n = 3)	S10 (n = 3)	
		S8 (n = 11)		
		S9 (n = 3)		
Impairment type		Hypertonia (n = 19)	Limb deficient (n = 32)	
		Athetosis (n = 2)	Impaired passive ROM (n = 2)	
		Impaired muscle power (n = 15)	Short stature (n = 2)	

[a]The S1 swimmer, two S3 swimmers, and one S5 swimmer who were tested in the supine position.

from video footage using standard two-dimensional video analysis procedures. The setup (shown in Fig. 1) allowed for acceleration and deceleration zones before and after the test zone respectively. Output from a 50-Hz video camera (Sony HDR HC9; Sony Corporation, Japan) placed perpendicular to the swimmers' direction of travel was captured and the 10-m swim time recorded to the nearest 0.02 s using commercial software (Dartfish TeamPro version 7.0; Dartfish UK). Participants performed three maximal effort 20-m freestyle sprints separated by a minimum of 3-min rest and the fastest time to cover the 10 m was used to compute their v_{MAX}.

Swimmers were towed by means of a drum winch, driven by a 0.75-kW electric motor (ABB Ltd, UK), located at the end of the swimming pool. This was controlled by a hand-held unit, enabling the towing speed to be set to ±0.01 m·s^{-1}. Swimmers were attached to the towing cable using a rubber belt around their upper torso. The towing force was measured via an in-line submersible load cell (DDEN; Applied Measurements Ltd, UK), which was attached approximately 5 m in front of the swimmer. More details of the setup and calibration of the load cell are provided in Oh et al. (5).

Data Collection and Processing

Passive drag. Passive drag was measured as swimmers were towed while holding a "passive" body position with their arms held by their side (Fig. 1). This position was necessary to enable the subsequent estimation of active drag (15). They were instructed to replicate the head position used during their prone or supine freestyle swim. Passive drag was measured at two towing speeds: v_{MAX} and v_{MAX} + 10% (v_{TOW}). The passive drag at these speeds is notated as D_{P_vMAX} and D_{P_vTOW}, respectively.

Active drag. Active drag was estimated using the Naval Architecture-Based Approach (NABA) proposed by Webb et al. (15). The swimmer was again towed at v_{TOW} but, in this case, they were instructed to swim freestyle at maximum effort. As they were being towed 10% faster than their maximal speed, they were also asked to increase their stroke rate proportionally; this tended to happen naturally due to the swimmer's faster motion through the water. The cable force during these assisted sprints (F_{TOW}) was recorded. As the towing speed was faster than the swimmer's v_{MAX}, the increased amount of drag was deducted using a correction value ($\Delta D_{Correction}$). $\Delta D_{Correction}$ was the difference in passive drag recorded at v_{MAX} (D_{P_vMAX}) and at the towed speed. The active drag (D_{A_vMAX}) at the swimmer's maximal speed was then calculated as:

$$D_{A\_vMAX} = F_{TOW} - \Delta D_{Correction} + D_{P\_vMAX} \quad [1]$$

For both active and passive drag (and for each speed), three trials were conducted with a minimum of 3-min rest between

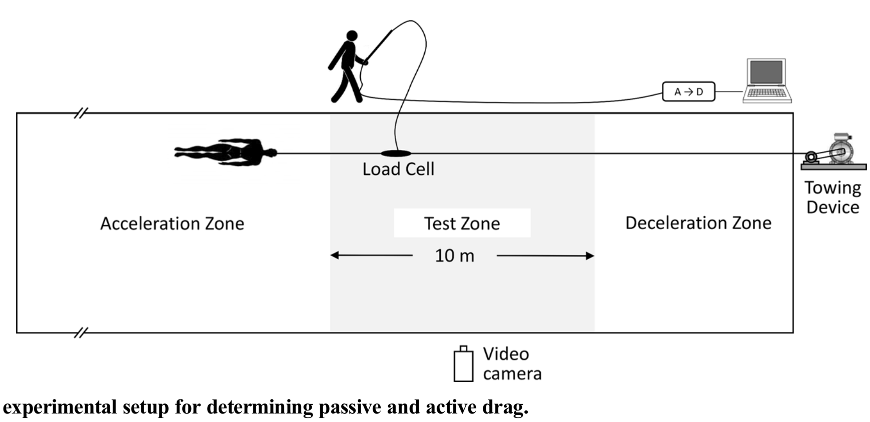

FIGURE 1—Plan view of experimental setup for determining passive and active drag.

trials. In each case, the lowest drag figure over the three trials was used in the subsequent analysis to reflect the lowest drag that the swimmer was able to achieve.

As hydrodynamic drag is related to the square of the towing or swimming speed (9,12), each swimmer's passive and active drag were divided by their v_{MAX} squared to allow interswimmer comparisons (equations 2 and 3). Hydrodynamic drag is also a function of body size (9). In passive drag studies, body size is often controlled for by considering the swimmer's frontal area (17), but this variable is not suitable for normalizing active drag as it changes constantly throughout the stroke cycle (18). In the current study, drag was expressed relative to BM; a measure of size that remains constant across the passive and active drag tests and that has been used previously to normalize drag (5). Normalized passive drag (D_{P_NORM}) and active drag (D_{A_NORM}) were, thus, calculated as follows:

$$D_{P\_NORM} = D_{P\_vMAX} / \left(BM \times v_{MAX}^2\right) \qquad [2]$$

$$D_{A\_NORM} = D_{A\_vMAX} / \left(BM \times v_{MAX}^2\right) \qquad [3]$$

Technique effectiveness ratio. A technique effectiveness ratio (TER) of the passive and active drag at v_{MAX} was calculated using the equation:

$$TER = D_{P\_vMAX} / D_{A\_vMAX} \qquad [4]$$

Where both active and passive drag are calculated at the same speed, as in the current study, the TER is identical to the thrust deduction (15) and the reciprocal of the technique drag index (12).

Statistical Analysis

All statistics were performed using R version 3.4.1 (R Core Team, 2017). Male and female data were combined for all analyses. Differences in drag between men and women (9) are not sex-related *per se*; rather, they are related to body size and swimming speed differences (19). Once these two factors have been accounted for (equations 2 and 3), any remaining drag differences between participants are assumed to be due primarily to non–sex-related factors (type and severity of impairment, skill level).

Shapiro–Wilk tests indicated nonuniform distribution of several measures for Para swimmers with physical impairment, so nonparametric tests were used for statistical analyses. Group differences in maximal swimming speed, normalized passive drag, normalized active drag, and TER between nondisabled swimmers, Para swimmers with anthropometric impairments (limb deficiency, short stature, impaired passive range of movement), and Para swimmers with central motor and neuromuscular impairments (athetosis, impaired muscle power, hypertonia) were determined using Kruskal–Wallis tests. Dunn tests were used *post hoc* using the Benjamini–Hochberg method to adjust for multiple comparisons to determine which groups showed differences when a main effect was found.

The strength of association of Para swimmers' maximal swimming speed, normalized passive drag, normalized active drag, and their TER, with their sport class was determined using Kendall's tau rank correlation coefficient, as sport classes represent ordinal data. A correlation was considered to be significant if $P < 0.05$. Correlations were defined as follows: weak, <0.3; moderate, 0.3–0.6; or strong, >0.6.

Spearman rank correlation coefficients were calculated to establish the strength of association between Para swimmers' maximal swimming speed and their normalized passive drag, normalized active drag, and TER. A correlation was considered significant if $P < 0.05$. Correlations were defined as follows: weak, <0.3; moderate, 0.3–0.6; or strong, >0.6. Correlation coefficients were calculated for the combined cohort of Para swimmers and separately for nondisabled swimmers, Para swimmers with anthropometric impairments and Para swimmers with central motor and neuromuscular impairment groups.

RESULTS

The maximal swimming speed of the participants ranged from 0.54 to 1.95 $m \cdot s^{-1}$ (mean, 1.38 $m \cdot s^{-1}$). Absolute passive drag and active drag forces at maximal speed ranged from 10.3 to 152.9 N (mean, 63.9 N) and 14.3 to 177.3 N (mean, 74.2 N), respectively. When normalized for swimming speed and BM, the passive drag and active drag force ranges were 0.35 to 0.78 m^{-1} (mean, 0.51 m^{-1}) and 0.38 to 1.08 m^{-1} (mean, 0.60 m^{-1}), respectively. The TER of the swimmers ranged from 0.48 to 1.07 (mean, 0.86).

Figure 2 presents maximal swimming speeds, normalized passive drag, normalized active drag, and TER stratified by type of physical impairment and by sport class. Kruskal–Wallis tests showed there was a statistically significant difference in maximal swimming speed (χ^2 (2) = 32.6, $P < 0.001$), normalized passive drag (χ^2 (2) = 8.6, $P = 0.01$), normalized active drag (χ^2 (2) = 11.4, $P < 0.01$), and TER (χ^2 (2) = 8.5, $P = 0.01$) between the different types of physical impairment. Para swimmers with anthropometric impairments (mean, 1.44 $m \cdot s^{-1}$; 1.15–1.75 $m \cdot s^{-1}$; $P < 0.01$) and central motor and neuromuscular impairments (mean, 1.19 $m \cdot s^{-1}$; 0.54–1.71 $m \cdot s^{-1}$; $P < 0.01$) had lower maximal swimming speeds than nondisabled swimmers (mean, 1.71 $m \cdot s^{-1}$; 1.54–1.95 $m \cdot s^{-1}$). Only Para swimmers with central motor and neuromuscular impairments showed higher normalized active drag (mean, 0.67 m^{-1}; 0.38–1.08 m^{-1} vs mean 0.56 m^{-1}; 0.48–0.70 m^{-1}; $P = 0.02$) and normalized passive drag (mean, 0.54 m^{-1}; 0.38–0.71 m^{-1} vs mean, 0.47 m^{-1}; 0.37–0.61 m^{-1}; $P < 0.01$) than the nondisabled swimmers. Para swimmers with central motor and neuromuscular impairments also showed lower maximal swimming speeds (mean, 1.19 $m \cdot s^{-1}$; 0.54–1.71 $m \cdot s^{-1}$ vs mean, 1.44 $m \cdot s^{-1}$; 1.15–1.75 $m \cdot s^{-1}$; $P < 0.01$), and higher normalized passive drag (mean, 0.54 m^{-1}; 0.38–0.71 m^{-1} vs mean, 0.50 m^{-1}; 0.35–0.78 m^{-1}; $P = 0.04$) and normalized active drag (mean, 0.67 m^{-1}; 0.38–1.08 m^{-1} vs mean, 0.56 m^{-1}; 0.39–0.81 m^{-1}; $P < 0.01$) than Para swimmers with anthropometric impairments.

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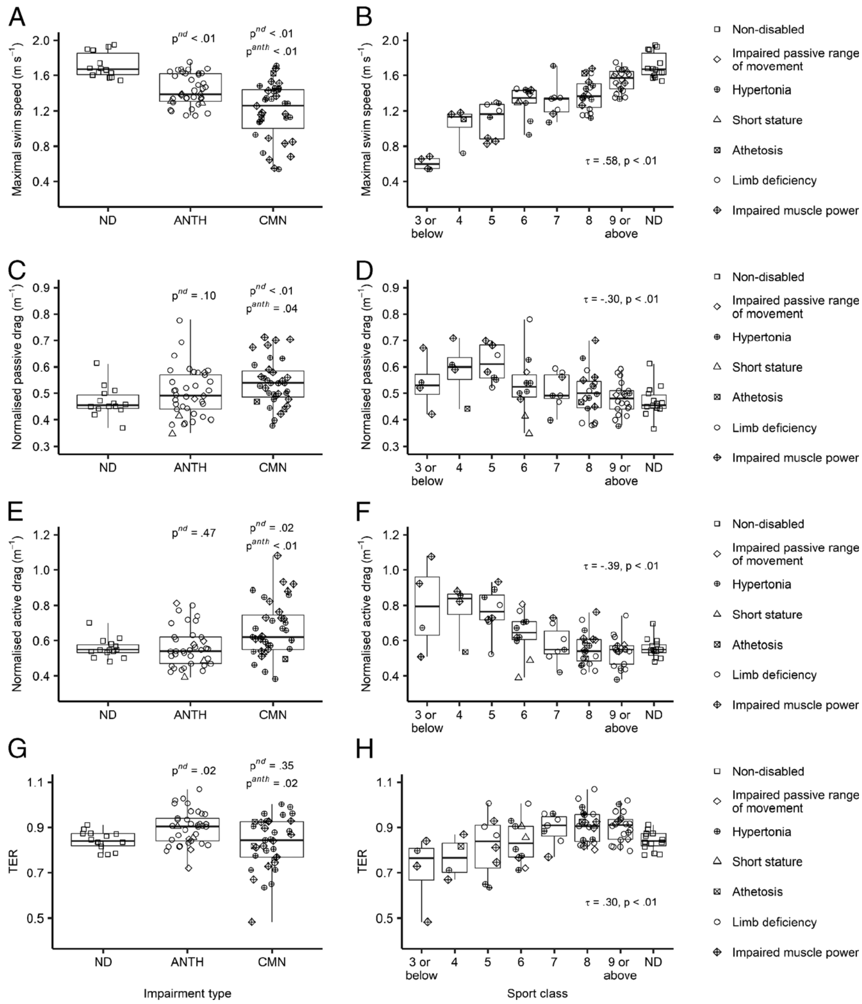

FIGURE 2—Boxplots showing maximal swimming speed (A, B), normalized passive drag, (C, D), normalized active drag (E, F), and TER (G, H). Left side plots are stratified by physical impairment type (ND, nondisabled; ANTH, anthropometric impairments; CMN, central motor and neuromuscular impairments); right side plots are stratified by sport (S) class.

There was a moderate, positive correlation found between swimmers' sport class and their maximal swimming speed (τ = 0.58, P < 0.01). Swimmers' sport class had a moderate correlation with their normalized passive drag (τ = −0.30, P < 0.01), normalized active drag (τ = −0.39, P < 0.01), and TER (τ = 0.30, P < 0.01). Para swimmers with central motor and neuromuscular impairments showed moderate correlations between sport class and normalized active drag (τ = −0.52, P < 0.01), normalized passive drag (τ = −0.29, P = 0.03), and TER (τ = 0.50, P < 0.01). There were no significant correlations found between sport class and normalized passive drag (τ = −0.18, P = 0.15), normalized active drag (τ = −0.11, P = 0.39), or TER (τ = −0.03, P = 0.80) in Para swimmers with anthropometric impairments.

No significant correlations were found between maximal swimming speed and normalized passive drag (r = −0.21, P = 0.08), normalized active drag (r = −0.22, P = 0.06), and TER (r = 0.14, P = 0.23) in the combined cohort of Para swimmers. There was a clear interaction between the type of physical impairment and the association between Para swimmers' maximal swimming speed and drag variables (Fig. 3). When analyzed independently, Para swimmers with central motor and neuromuscular impairments showed moderate negative correlations between maximal swimming speed and normalized passive drag (r = −0.40, P = 0.02) and normalized active drag (r = −0.50, P < 0.01), and a moderate positive correlation between maximal swimming speed and their TER (r = 0.35, P = 0.05). Para swimmers with anthropometric impairments showed the inverse for the association between maximal swimming speed and normalized active drag (r = 0.36, P = 0.03), normalized passive drag (r = 0.16, P = 0.35) and TER (r = −0.27, P = 0.11). There were strong correlations found between normalized active drag and normalized passive drag in the entire participant cohort (r = 0.86, P < 0.01) and for Para swimmers with anthropometric (r = 0.85, P < 0.01) or central motor and neuromuscular impairments (r = 0.80, P < 0.01).

DISCUSSION

The primary aim of this study was to quantify active and passive drag in Para swimmers and evaluate the strength of

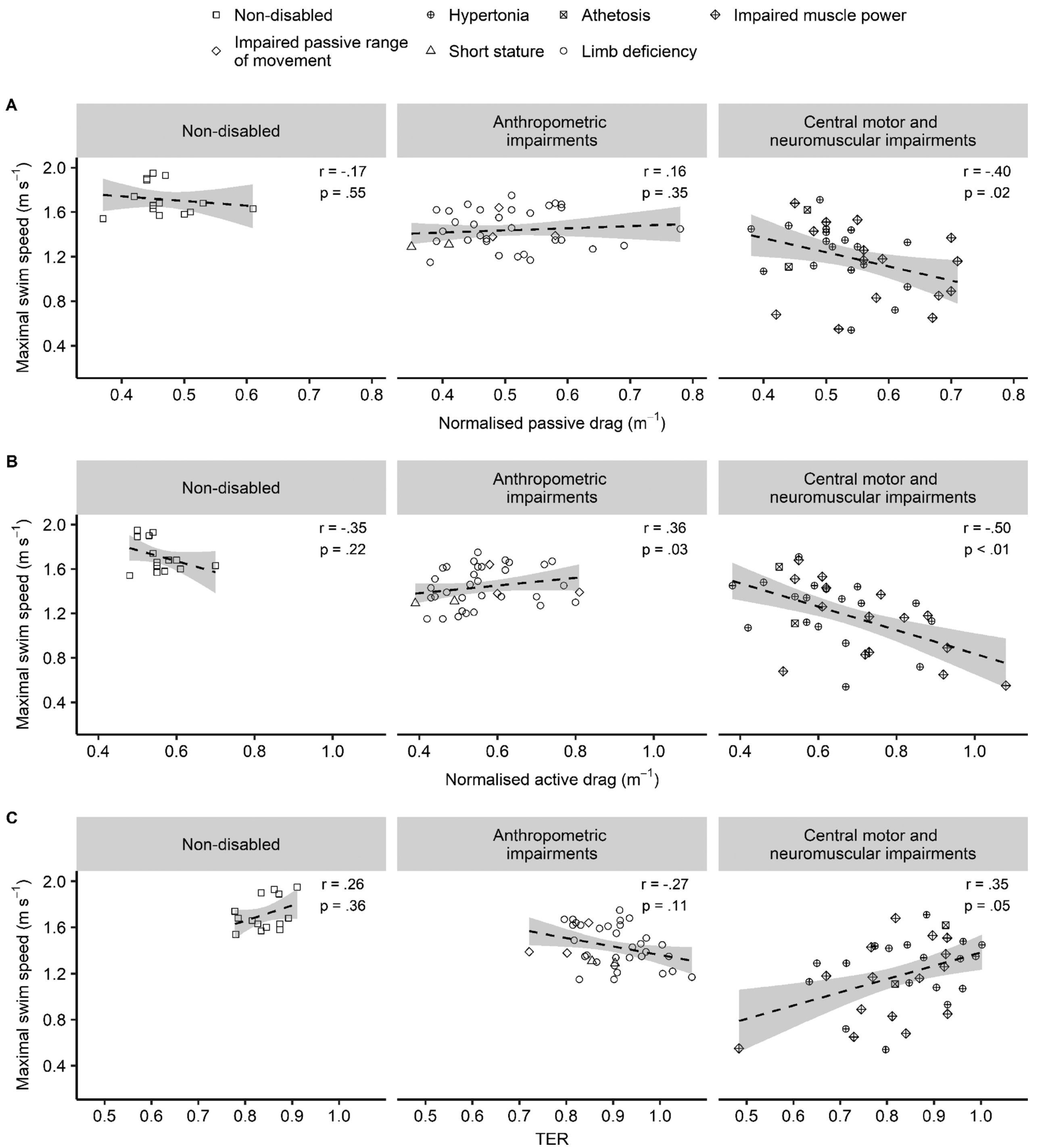

FIGURE 3—Scatterplots showing relationships between maximal swimming speed and (A) normalized passive drag, (B) normalized active drag, and (C) TER for the nondisabled group (*left side plots*); anthropometric impairment group (*middle plots*), and central motor and neuromuscular impairment group (*right side plots*).

association between these measures and type of physical impairment, freestyle swimming performance and sport class. This work was done to evaluate whether drag measures are suitable criteria for classification in Para swimming. The key finding of this study was that active and passive drag were only determinants of maximal freestyle swimming speed in Para swimmers with central motor and neuromuscular impairments. These drag measures did not explain activity limitation within the Para swimmers with anthropometric impairments. This indicates that classification should be different for these two groups, at least with regard to consideration of drag.

Unlike passive drag, active drag cannot be measured directly. Several popular methods for estimating active drag were considered for this study. The Measuring Active Drag approach (20) involves measuring hand push-off forces using underwater pads linked to a load cell. However, the

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requirement to make contact with the pads may affect stroke mechanics (6), and this approach would not have accommodated many of participants in the current study. In the Velocity Perturbation Method (12), the swimmer tows a small hydrodynamic body of known drag. The maximal speed when swimming with the hydrodynamic body is then compared with the maximal free swimming speed. A similar assisted towing method (ATM) was later proposed (18) which entails the swimmer being assisted by a towing machine rather than resisted. The validity of some of the theoretical assumptions underpinning these two methods has been challenged (21) and violation of these assumptions has been shown to produce substantial errors in the calculated drag (22). Consequently, these methods were discounted. The method chosen to estimate active drag, the NABA, is an adaptation of a model scale self-propulsion experiment for ships (15,23). As the NABA has been found to produce comparable active drag values to the ATM, but significantly more repeatable results which are less sensitive to experimental error (15,24), it was selected for use in this study.

The active drag range (14.3–135.3 N) and maximal swimming speed range (0.54–1.75 $m \cdot s^{-1}$) for the Para swimmers in this study were much larger than those typically reported in studies of nondisabled swimmers (9,12,14,20). This was anticipated given the heterogeneous nature of the Para swimmer cohort which comprised individuals with physical impairments varying in type and severity. The mean active drag of the nondisabled swimmers was 113.2 N at a mean maximal swimming speed of 1.71 $m \cdot s^{-1}$. This is higher than previously reported for trained swimmers tested at a similar speed (1.68 $m \cdot s^{-1}$) on the MAD system (82.3 N) but lower than the mean of 148.3 N obtained for the same swimmers tested at the same speed using the ATM (25). Comparisons of active drag values between studies should be made with caution because it is inevitable that methodological differences may account for some of the apparent differences in active drag.

Relationship between drag and sport class. Normalized passive drag had a significant moderate negative association with sport class. Although this result supports the findings of a previous study (5), the correlation was not as strong as reported in that case ($\tau = -0.30$ vs $\tau = -0.60$). This might be because the current study assessed passive drag while swimmers had their arms by their sides, rather than above their head as in the study by Oh et al. (5), and this position may mask some of the impact that impairments have. Normalized passive drag also had a strong positive association with normalized active drag, which was anticipated as the NABA considers passive drag to be a large component of the active drag.

The hypothesis that there would be an inverse relationship between Para swimmers' normalized active drag and their sport class was accepted. As the severity of swimming-specific impairment increased, so did the amount of drag created when swimming. This can mostly be attributed to increasing passive drag with greater swim-specific impairment, because there was a strong association between normalized active and passive drag variables ($r = 0.86$, $P < 0.01$). There were more apparent differences in TER for sport classes below S7 indicating a disassociation between active and passive drag for Para swimmers with severe physical impairments, particularly central motor and neuromuscular impairments (Fig. 2H). Active drag is affected by technical ability as well as impairment. This was not thought to have a material impact on the results as the participants were all elite swimmers and therefore all highly skilled. For these swimmers, impairments that affect limb range of motion and coordination during their freestyle swim stroke might cause relatively higher active drag that impacts their swim performance.

Technique effectiveness ratio. The hypothesis that Para swimmers' TER would be positively related to their sport class was accepted. This indicates that the more severely impaired athletes created relatively more disturbance to the water when swimming compared with the less impaired swimmers. It is interesting to note that two of the double-leg amputees produced less drag when swimming freestyle than when being passively towed, resulting in TER greater than one. It was also notable that swimmers with arm-amputations tended to have TER below the group mean, whereas swimmers with double-leg amputations had TER above it. One explanation for this would be the absence of a leg-kick action in the double leg amputees. A front crawl flutter kick is beneficial to performance but may increase active drag due to the disturbance it causes to the water. This might explain the trend of swimmers in the higher sport classes (≥S7) having a higher TER than nondisabled swimmers (Fig. 2H). A second possible explanation can be found by considering the effect of the Froude Number (Fr).

Froude number. Wave drag is the energy required to create the waves and form a wake behind the swimmer (26). It depends on Fr, which is expressed as $Fr = v / \sqrt{(gL)}$ where v is the swimming speed, g is gravity, and L is the length of the swimmer. Thus, at a given speed, double-leg amputee swimmers will be affected by wave drag to a greater extent than Para swimmers with intact legs due to the differences in L. Passive drag was measured with the arms held beside the body and so the Fr in the passive trials relates to the swimmers' standing height. In the active swimming trials, all the Para swimmers effectively increased L due to the arms being stretched overhead. Consequently, the Fr in the swimming trials would be related to the swimmers' streamlined height, potentially causing the wave drag component during active swimming to be lower than during passive towing. The double leg amputees could benefit more from this phenomenon than the non–leg-amputee swimmers because they had a greater percentage increase from standing to streamlined height, and consequently, a greater drop in Fr. Therefore, a swimmer's physical impairment can directly influence the relationship between their passive and active drag. Thus, the TER is not a valid universal measure for evaluating Para swimmers' technical effectiveness. Nevertheless, it may potentially be used to assess the technical improvement of an individual over time or to compare Para swimmers with similar physical impairments.

Active drag and impairment type. It was hypothesized that certain impairment types would be more predisposed to creating high active drag forces. Our results showed that type of physical impairment interacts with the relationship between active drag measures, sport class, and freestyle swimming performance. Normalized active drag, normalized passive drag, and TER all had moderate associations with sport class for Para swimmers with central motor and neuromuscular impairments, but not for Para swimmers with anthropometric impairments. Para swimmers with central motor and neuromuscular impairments make up the majority of the lower sport classes (<S7) that are most affected by higher passive and active drag (Figs. 2C and E). Unlike Para swimmers with anthropometric impairments, there were moderate, negative correlations between sport class and drag variables in these swimmers, suggesting that their impairments cause higher active and passive drag with increasing severity of impairment as defined by the current classification system. Active and passive drag were shown to be key determinants of maximal swimming speed in these swimmers ($r = -0.50$ to -0.40, $P \leq 0.02$). Additionally, a moderate, positive correlation found between maximal swimming speed and TER ($r = 0.35$, $P = 0.05$) suggests that central motor and neuromuscular impairments impact on a swimmer's ability to interact with the water during the swim stroke, rather than solely affecting their passive drag. These results suggest that it is important to consider active and passive drag in classifying Para swimmers with central motor and neuromuscular impairments.

Para swimmers with anthropometric impairments were found to have similar normalized active and passive drag values to nondisabled swimmers and did not show a significant correlation between drag variables and sport class. This suggests that Para swimmers with anthropometric impairments are primarily limited by their ability to produce propulsion rather than their impairments causing high active or passive drag. In fact, normalized active drag was found to have a moderate, positive correlation with maximal swimming speed in these Para swimmers ($r = 0.36$, $P = 0.03$). As discussed previously, it is possible that these swimmers create less disturbance in the water with increasing severity of impairment due to partial or full absence of a leg-kick or arm stroke during freestyle swimming. This might further explain the finding that Para swimmers with anthropometric impairments had higher TER values than nondisabled swimmers and Para swimmers with central motor and neuromuscular impairment (Fig. 2G). It appears that several swimmers with anthropometric impairment do have higher active and passive drag than nondisabled swimmers (Fig. 2C and Fig. 2E). However, the fact that normalized active and passive drag do not explain activity limitation within this group suggests that it would be erroneous to consider these measures during their classification. It is also important to consider whether BM, body length, frontal area, or body surface area are used for normalization because these measures are affected differently by the nature of impairment (e.g., for a leg amputee, BM, body length, and surface area will be greatly reduced, whereas frontal area is unaffected). Further research is required to ascertain whether normalization techniques modulate the relationship between drag and performance for swimmers with anthropometric impairments, or if their activity limitation is explained mostly by other determinants related to swimming propulsion.

Implications. The current study, together with the study by Oh et al. (5), demonstrates that, within sport classes, Para swimmers have a range of levels of both active and passive drag. This is mainly because different impairment types compete within a single class, and this appears to give some swimmers a substantial advantage when competing. However, active and passive drag were only found to be determinants of maximal freestyle swim speed in Para swimmers with central motor and neuromuscular impairments. Although several Para swimmers with anthropometric impairment were found to have higher active and passive drag than nondisabled swimmers, these measures did not explain activity limitation within this group.

This research suggests that taking an impairment-specific approach is important for understanding the impact of physical impairment on sports performance, thereby informing classification in Para swimming. Classification methods should be different for these two groups. Active drag measures should be included in revised Paralympic swimming classification for Para swimmers with central motor and neuromuscular impairments, but not for Para swimmers with anthropometric impairments.

This study has demonstrated that the impact of central motor and neuromuscular impairments on an important determinant of swimming performance (drag) is substantively different to the impact caused by anthropometric impairments. This raises the prospect that the effects of these two impairments are not comparable and, to help achieve fair and equitable competition, these groups should compete separately.

Limitations. The method used to obtain active drag has some inherent assumptions that must be acknowledged. In particular, it was assumed that the swimmers' front crawl technique, when being towed 10% faster than their maximal swimming speed, was not materially different from their nontowed technique and that they were able to maintain the same propulsive efficiency or "advance ratio" (20) in both conditions. All assessments were done while swimmers held their breath so this study does not allow for differences in active drag due to variations in breathing technique, which would also be expected to be influenced by swimmers' physical impairments. It is also important to acknowledge that as the current Para swimming classification system is not evidence-based, the assumption that Para swimmers within the same sport class have approximately the same levels of activity limitation may be disputable.

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REFERENCES

1. Tweedy SM, Vanlandewijck Y. International Paralympic committee position stand—background and scientific principles of classification in Paralympic sport. *Brit J Sports Med*. 2011;45(4):259–69.
2. IPC Swimming. Swimming classification manual. February 2005. [Internet]. Available from: http://www. paralimpicos.es/web/2008PEKPV/deportes/natacion/clasificacion.pdf (accessed November 2019).
3. Toussaint HM, Beek PJ. Biomechanics of competitive front crawl swimming. *Sports Med*. 1992;13(1):8–24.
4. www.paralympic.org [Internet]. Available from: www.paralympic.org/news/ipc-swimming-launches-classification-review (accessed November 2019).
5. Oh Y-T, Burkett B, Osborough C, Formosa D, Payton CJ. London 2012 Paralympic swimming: passive drag and the classification system. *Brit J Sports Med*. 2013;47(13):838–43.
6. Sacilotto GB, Ball N, Mason BR. A biomechanical review of the techniques used to estimate or measure resistive forces in swimming. *J Appl Biomech*. 2014;30(1):119–27.
7. Barbosa TM, Costa MJ, Morais JE, et al. Characterization of speed fluctuation and drag force in young swimmers: a gender comparison. *Hum Mov Sci*. 2013;32(6):1214–25.
8. Seifert L, Schnitzler C, Bideault G, Alberty M, Chollet D, Toussaint HM. Relationships between coordination, active drag and propelling efficiency in crawl. *Hum Mov Sci*. 2015;39(1):55–64.
9. Toussaint HM, De Groot G, Savelberg HH, et al. Active drag related to velocity in male and female swimmers. *J Biomech*. 1988;21(5):435–8.
10. Figueiredo P, Willig R, Alves F, Vilas-Boas JP, Fernandes RJ. Biophysical characterization of a swimmer with a unilateral arm amputation: a case study. *Int J Sports Physiol Perform*. 2014;9(6):1050–3.
11. Kjendlie PL, Stallman RK. Drag characteristics of competitive swimming children and adults. *J Appl Biomech*. 2008;24(1):35–42.
12. Kolmogorov SV, Duplishcheva OA. Active drag, useful mechanical power output and hydrodynamic force coefficient in different swimming strokes at maximal velocity. *J Biomech*. 1992;25(3):311–8.
13. Marinho DA, Barbosa TM, Costa MJ, et al. Can 8-weeks of training affect active drag in young swimmers? *J Sports Sci Med*. 2010;9(1):71–8.
14. Toussaint HM. Differences in propelling efficiency between competitive and triathlon swimmers. *Med Sci Sports Exerc*. 1990;22(3):409–15.
15. Webb A, Banks J, Phillips C, Hudson D, Taunton D, Turnock S. Prediction of passive and active drag in swimming. *Procedia Eng*. 2011;13:133–40.
16. Tweedy SM, Mann D, Vanlandewijck YC. Research needs for the development of evidence-based systems of classification for physical, vision, and intellectual impairments. In: Vanlandewijck YC, Thompson WR, editors. *Training and Coaching the Paralympic Athlete*. Chichester. UK: John Wiley & Sons; 2016. pp. 122–49.
17. Vilas-Boas JP, Costa L, Fernandes RJ, et al. Determination of the drag coefficient during the first and second gliding positions of the breaststroke underwater stroke. *J Appl Biomech*. 2010;26(3):324–31.
18. Alcock A, Mason B. Biomechanical analysis of active drag in swimming. In: *Proceedings of the 25th International Symposium on Biomechanics in Sports*. Ouro Preto (Brazil); 2007. pp. 212–5.
19. Huijing PA, Toussaint HM, Clarys JP, et al. Active drag related to body dimensions. In: Ungerechts BE, Reischle K, Wilke K, editors. *Swimming Science V*. Champaign: Human Kinetics; 1988. pp. 31–7.
20. Hollander AP, De Groot G, van Ingen Schenau GJ, et al. Measurement of active drag during crawl arm stroke swimming. *J Sports Sci*. 1986;4(1):21–30.
21. Toussaint HM, Roos PE, Kolmogorov S. The determination of drag in front crawl swimming. *J Biomech*. 2004;37(11):1655–63.
22. Hazrati P, Sinclair PJ, Spratford W, Ferdinands RE, Mason BR. Contribution of uncertainty in estimation of active drag using assisted towing method in front crawl swimming. *J Sports Sci*. 2018;36(1):7–13.
23. Molland AF, Turnock SR, Hudson DA. *Ship Resistance and Propulsion: Practical Estimation of Propulsive Power*. Cambridge (NY): Cambridge University Press; 2011. pp. 151–5.
24. Oh Y-T. *Passive and active drag of paralympic swimmers [dissertation]*. Manchester (England): Metropolitan University; 2015. 188.
25. Formosa DP, Toussaint HM, Mason BR, Burkett B. Comparative analysis of active drag using the MAD system and an assisted towing method in front crawl swimming. *J Appl Biomech*. 2012;28(6):746–50.
26. Vennell R, Pease D, Wilson B. Wave drag on human swimmers. *J Biomech*. 2006;39(4):664–71.