Passive drag in Para swimmers with physical impairments: Implications for evidence-based classification in Para swimming

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Abstract

The inherent hydrodynamic resistance force, or passive drag, of a swimmer directly influences how they move through the water. For swimmers with physical impairments the strength of association between passive drag and swimming performance is unknown. Knowledge on this factor could improve the World Para Swimming classification process. This study established the relationship between passive drag and 100 m freestyle race performance in Para swimmers with physical impairments. Using a cross-sectional study design, an electrical-mechanical towing device was used to measure passive drag force in 132 international-level Para swimmers. There was a strong, negative correlation between normalised passive drag force and 100 m freestyle race speed in the combined participant cohort ($\rho = -0.77$, $P < 0.001$). Type of physical impairment was found to affect the relationship between passive drag and 100 m freestyle race speed when included in linear regression ($R^2 = 0.65$, $\chi^2 = 11.5$, $P = 0.025$). These findings contribute to the body of evidence that passive drag can provide an objective assessment of activity limitation in Para swimmers with physical impairments. The effect of physical impairment type on the relationship between passive drag and swimming performance should be accounted for in Para swimming classification.

Keywords: Paralympics, Para sport, classification, disability, streamline, gliding.

Introduction

Para swimming is one of the most popular sports for people with disabilities and has been part of the Paralympic games since the inaugural games in Rome, 1960. Classification systems are integral in enabling fair competition in Para sport with Para swimming having used a functional classification system since the 1992 Barcelona Games. For Para swimmers with one of the eight eligible physical impairments, a dry-land assessment and an in-water technical assessment is used to determine eligibility and assign them a sport class in which they compete.[1] Both the dry-land and in-water technical assessments incorporate qualitative methods that are subjective and do not comply with best practice.[2,3] The in-water technical assessment, for example, consists of athletes swimming multiple distances at different speeds as classifiers subjectively assign separate body segments a score from 0 to 5, with lower numbers indicating greater activity limitation. The efficacy of the subjective assessment of activity limitation and the weighting and aggregation of point scores for different body segments has been questioned.[2,4,5] Research that identifies quantitative tests that objectively measure the impact of impairment on the determinants of swimming performance can help to advance Para swimming classification.

A swimmer's performance is fundamentally determined by the relationship between the propulsive force that they generate and the resistive drag force they encounter as they move through the water.[6] Evaluation of these two performance determinants, propulsion and drag, should be central to the technical assessment for Para swimmers with an eligible physical impairment.[7-9] The most efficient way to reach and maintain maximal swim speed is by minimising resistive drag.[10,11] Drag is the sum of three resistance components (viscous pressure resistance, wave making resistance and skin friction resistance) which are each influenced by swimmers' morphological characteristics and the speed and orientation of their body parts as they move through water.[12,13] It is predicted that for a streamlined swimmer on the water surface at a speed of 1.55 $m \cdot s^{-1}$, wave making resistance and viscous pressure resistance contribute 59% and 33%, respectively to the total drag; the remaining 8% coming from skin friction resistance.[14] Thus the impact of physical impairment on swimming drag is most likely to be explained by an increase in one or both of the first two resistance components.

Viscous pressure resistance is caused by a pressure differential between the leading and trailing edges of the body.[12,13] This drag component is particularly influenced by the cross-sectional area of the swimmer in the direction of flow and so is associated with anthropometric parameters[15,16] and the orientation of body parts during the swim stroke.[17,18] It is expected that Para swimmers whose physical impairments limit their ability to achieve and maintain a streamlined body position during gliding, or while performing a swim stroke, will experience greater viscous pressure resistance at a given speed than swimmers without impairment.

Wave making resistance is the resistance encountered due to the energy required to lift water against gravity and make waves on the surface.[13] This drag component relates to the length of the body as described by the Froude number and has a cubic relationship with swim velocity.[13] This explains why stature is associated with swimming aptitude, particularly in the faster, shorter distance events,[19] and how swimmers can reduce drag by extending their arms above their head in a streamlined position to increase their body length.[13,16] Para swimmers with physical impairments that cause a decrease in stature (e.g. bilateral lower limb deficiency, achondroplasia) might be susceptible to experiencing greater wave making resistance when swimming on the surface.

The measurement of drag in swimming can be determined under two conditions. Active drag is the resistance that swimmers experience when performing a swim stroke; it has been estimated using several experimental approaches although the measurement of active drag remains a controversial issue.[14,20] Swimmers that perform arm and leg actions that create less disturbance of the water are considered to have a more efficient swimming technique than those swimmers that create more disturbance of the water and have higher active drag despite achieving similar swim velocities.[8,14] Passive drag is the resistance that a swimmer experiences when moving through the water while holding a fixed body position and can be measured directly.[21] Desired morphological changes with training might reduce passive drag because it is dependent on body shape and size,[15] although passive drag is largely independent of skill and is influenced more by experimental conditions including the speed, depth and position of the swimmer.[21]

Research has demonstrated the potential of active and passive drag assessments in estimating activity limitation caused by eligible physical impairments in Para swimming.[8,9,22] Data collected in 113 Para swimmers at the 2012 London Paralympics showed passive drag collected in the most streamlined body position had a strong correlation with sport class.[9] Para swimmers in the lower sport classes (i.e. those with the greatest swim-specific impairment) had higher passive drag than swimmers in the higher sport classes, although there was considerable within-class variability within some classes suggesting certain swimmers might be disadvantaged by the classification system. The results of this study suggest that limitations in motor function (i.e. strength, motor coordination, and range of movement) or reductions in limb length and surface area limit the ability of some Para swimmers to achieve a streamlined body position in the water that will impact the glide phases of the starts, turns and within stroke cycles of breaststroke.[12,23] However, there is a strong association between normalised active and passive drag forces in this cohort suggesting that swimmers' physical impairments also impact their ability to maintain an efficient body position during the propelling phases of the stroke cycle in free swimming.[8]

More recently, active drag estimated using an assisted towing method has been shown to be correlated with maximal freestyle race speed in Para swimmers with impaired muscle power, hypertonia, athetosis and ataxia, but not for Para swimmers with limb deficiency and short stature.[8] This finding might explain the large within-class variability in passive drag within some sport classes because different types of physical impairment compete within the same sport class despite their impairments having a dissimilar impact on the determinants of swimming performance. Incidentally, this study also reported on the passive drag in the cohort, which was necessary to estimate active drag and was assessed at or above maximum swim speeds with swimmers holding a fixed body position with their arms by their side.[8,14] There was a moderate negative correlation between normalised passive drag and sport class (τ = -0.3, $p < 0.01$), although this relationship was not as strong as previously reported by Oh et al.[9] (τ = -0.6, $p < 0.01$) and normalised passive drag had a weak correlation with maximal freestyle swim speed in the cohort ($r = -0.21$, $p = 0.08$). It was postulated that the body position in which swimmers' passive drag was assessed, with their arms by their side, masked some of the impact that their impairments have on swimming performance. Passive drag assessed with swimmers in their most streamlined body position might better explain the activity limitation caused by their physical impairment compared to passive drag assessed with arms by the side.

Passive drag has been proposed as an objective assessment of activity limitation to guide classification of Para swimmers with physical impairments.[9] However, there is no published research on passive drag in the most streamlined body position in Para swimmers with specific types of physical impairment, and no published research that has established the relationship between passive drag in the most streamlined body position and swim performance in this cohort. There is evidence that the relationships between performance determinants are dependent on the type of physical impairment and an impairment-specific approach should be taken to validate classification methods in Para swimming.[8] Therefore, the aim of this study was two-fold: (a) to establish the relationship between passive drag in the most streamlined body position and freestyle swim performance in Para swimmers with physical impairments, and (b) to determine the influence, if any, of type of physical impairment on this relationship. It was hypothesised that there would be a negative correlation between passive drag and freestyle swim performance in Para swimmers with physical impairment, and that the type of physical impairment affects the relationship between passive drag and freestyle swim performance.

Materials and methods

A cross-sectional study was conducted in a cohort of 132 Para swimmers with an eligible physical impairment (Table 1). Participants had received international classification, were undertaking planned training regimes and were listed on the World Para Swimming Classification Master List. Participants were of an international standard having competed at a Paralympic games or World Para Swimming Championships in the calendar year that they participated in this study. Testing procedures were approved by the Manchester Metropolitan University Human Research Ethics Committee. All participants provided their written informed consent to participate in this study.

Passive drag 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 details of experimental procedures used in this study have been detailed previously.[9] Participants were towed on the surface at 1.5 $m \cdot s^{-1}$ using an electrical-mechanical towing rig which comprised a drum winch driven by a 0.75 kW electric motor and a speed controller with a resolution of ±0.01 $m \cdot s^{-1}$. Participants were attached to an inelastic steel cable; an in-line submersible load cell attached approximately 5 m in front of the swimmer recorded the cable force as they were being towed. The load cell was connected to a 12-bit analog-digital converter that sampled force data at 100 Hz with a resolution of 0.25 N.

Participants were towed in their preferred swim costume and cap. Participants were attached to the towing cable by holding onto a small handle, a belt secured around their upper torso, or thin rubber tubing of negligible buoyancy wrapped around the upper arms depending on the nature of their impairment. Participants were instructed to hold their most streamlined prone position and hold their breath as they were being towed. Between three and six trials were recorded for each participant over approximately 20 to 35 m. A time window of at least 4 s duration in which the cable force was most stable was identified and the mean passive drag force value was calculated. The lowest drag value for each participant was used for subsequent analyses. To account for the anthropometric profile between participants of different size, the passive drag force was normalised to body mass on the assumption that mass was a suitable variable for reflecting a swimmer's size.[8,9] Body mass was collected prior to testing using calibrated scales. Passive drag was also expressed as a resistive factor to account for the effect of towing velocity on hydrodynamic drag by dividing the passive drag force by the towing velocity squared.[8,21]

Participants' annual best 100 m freestyle race times were obtained from a public website (https://www.paralympic.org/swimming/rankings) and used as a criterion measure of swim performance. All race times were from long course swim meets and were subject to verification with the World Para Swimming Classification Master List. Only race times in the same calendar year as passive drag assessment were included. Mean race speed was calculated using recorded times and used in analyses.

Statistics were performed using R version 3.6.2.[24] Shapiro-Wilks tests showed data were non-normally distributed. Spearman rank correlation coefficients (ρ) were calculated to determine the strength of association between normalised passive drag ($N \cdot kg^{-1}$) and 100 m freestyle performance ($m \cdot s^{-1}$). Correlations were calculated for the entire cohort and separately for each type of physical impairment. A correlation was considered significant if $P \leq 0.05$ and defined as weak ≤ 0.29, moderate 0.3 – 0.59 or strong ≥ 0.6. Linear regression models were trained to establish the relationship between normalised passive drag ($N \cdot kg^{-1}$) with 100 m freestyle performance ($m \cdot s^{-1}$) and determine the influence of physical impairment type. The natural logarithm of normalised passive drag was included in linear regression to model the curvilinear relationship with 100 m freestyle performance. A stepwise procedure was used to examine the effect of sex and physical impairment type in multiple linear regression. Sex was first included in linear regression because male and female swimmers were pooled for analyses. The type of physical impairment was then included as an effect term, and then as an interaction term in linear regression to test the influence of physical impairment type on the relationship between passive drag and freestyle performance. At each iteration a log likelihood ratio test was used to determine if the increase in model complexity explained a significantly greater amount of variance in 100 m freestyle performance. The coefficient of determination (R^2) and root-mean-square error (RMSE) were calculated to appraise regression models.

Results

At a constant tow velocity of 1.5 $m \cdot s^{-1}$ the absolute passive drag force ranged from 25 to 120 N (median, 47 N), and the passive drag force normalised to body mass ranged from 0.45 to 2.03 $N \cdot kg^{-1}$ (median, 0.72 $N \cdot kg^{-1}$). These values expressed as a resistive factor to account for the effect of velocity on drag force ranged from 11.1 to 53.3 $kg \cdot m^{-1}$ (median, 20.8 $kg \cdot m^{-1}$) and 0.2 to 0.9 m^{-1} (median, 0.32 m^{-1}), respectively. Table 1 presents the absolute and normalised passive drag forces and factors for Para swimmers stratified by physical impairment type.

There was a strong, negative correlation ($\rho = -0.77$, $P < 0.001$) between normalised passive drag force and 100 m freestyle race speed for the combined participant cohort showing faster swimmers have lower passive drag normalised to their body mass (Figure 1). The strong, negative correlation between passive drag and performance was evident for all the physical impairment groups ($\rho = -0.65$ – -0.86, $P < 0.001$), except for Para swimmers with short stature ($\rho = -0.56$, $P = 0.07$). However, the strength of correlation improved in Para swimmers with short stature ($\rho = -0.66$, $P = 0.04$) after the removal of an outlying case.

The natural logarithm of normalised passive drag force explained 62% of the variance in 100 m freestyle performance in the participant cohort ($b_0 = 1.09$, $b_1 = -0.89$, $R^2 = 0.62$, RMSE = 0.22, $P < 0.001$). Wilcoxon rank sum tests showed male participants were more likely to have higher 100 m freestyle race speeds (median, 1.46 $m \cdot s^{-1}$ versus 1.22 $m \cdot s^{-1}$, $W = 2832$, $P < 0.001$) and lower normalised passive drag (median, 0.69 $N \cdot kg^{-1}$ versus 0.84 $N \cdot kg^{-1}$, $W = 1616$, $P = 0.036$) than female participants (Figure 2). Sex was found to affect the relationship between passive drag and 100 m freestyle race speed and increased the deviance explained by linear regression ($R^2 = 0.64$, RMSE = 0.21, $\chi^2 = 7.2$, $P = 0.007$); the constant of regression was higher for men ($b_0 = 1.14$) than for women ($b_0 = 1.04$). There was a further increase in the amount of deviance explained when including the physical impairment type as an effect term in regression (R^2 = 0.67, RMSE = 0.2, χ^2 = 10.4, P = 0.03), but there were no further improvements in model parsimony when including physical impairment type as an interaction term (R^2 = 0.68, RMSE = 0.2, χ^2 = 4.6, P = 0.33). This result shows that physical impairment type accounts for a significant and independent portion of deviance in linear regression, and that the exclusion of sex is unlikely to overestimate the variance explained by physical impairment type in the model.

Sex was removed from the model to interpret the effect of physical impairment type on the relationship between passive drag and 100 m freestyle race speed (Figure 2, R^2 = 0.65, RMSE = 0.2, P = 0.005). There was a similar constant for regression in Para swimmers with hypertonia, ataxia and athetosis (b_0 = 1.032), impaired muscle power (b_0 = 1.035, P = 0.97), impaired passive range of movement (b_0 = 1.046, P = 0.86), and short stature (b_0 = 1.11, P = 0.32). The constant was higher in Para swimmers with limb deficiency (b_0 = 1.164) showing these swimmers have faster 100 m freestyle race speeds for a given unit of normalised passive drag force than Para swimmers with hypertonia, ataxia and athetosis (B = -0.131, P = 0.009), impaired muscle power (B = -0.129, P = 0.012) and impaired passive range of movement (B = -0.118, P = 0.08). The constant of regression was similar for Para swimmers with limb deficiency and short stature (B = -0.054, P = 0.45).

Discussion

This study aimed to establish the relationship between passive drag and 100 m freestyle swim performance in Para swimmers with an eligible physical impairment and determine whether the type of physical impairment influences this relationship. The main finding is that normalised passive drag has a strong, negative association with 100 m freestyle race speed in Para swimmers with physical impairment. In other words, Para swimmers that have lower passive drag relative to their body mass also tend to have faster times in the 100 m freestyle. However, linear regression showed that type of physical impairment influenced the relationship between passive drag and 100 m freestyle race performance. These findings suggest that passive drag is a determinant of performance and can be used to provide an objective assessment of activity limitation in Para swimmers with physical impairments although it is important to consider the type of physical impairment when applying results to guide classification.

There was large variability in the passive drag force recorded in the participant cohort, with values ranging from 25 N to 120 N. This corresponds with previous research in Para swimmers [9] and was expected due to participants having various types and severity of physical impairment and despite them being highly trained, international-level Para swimmers. The median passive drag forces recorded for each of the physical impairment groups were similar, ranging from 45 N to 53 N, and the interquartile range in passive drag within each physical impairment group tended to increase with interquartile range of sport class (Table 1). The median passive drag forces were more different between the physical impairment groups when values were normalised to body mass, suggesting the type of impairment influences the relationship between body mass and passive drag force due to differences in anthropometric profiles.

For the purpose of classification, the objective of passive drag assessment should be to determine the interaction between Para swimmers' impairments, their body shape and position in the water, and the amount of drag they experience. The body size (i.e. mass, stature and frontal area) of non-disabled swimmers has been shown to influence the passive drag they experience, and so it is common to calculate the coefficient of drag using swimmers' frontal area when evaluating their gliding efficiency.[12,16] In this study, passive drag forces were normalised to body mass to account for body size because it provides an approximation of the deceleration that swimmers would experience if the towing force were removed and has the advantage of remaining constant throughout assessment. It should be noted however, that two swimmers with equal normalised passive drag might decelerate at different rates during a glide because of varied body shape and size that affect added mass.[12] Nevertheless, expressing passive drag force relative to body mass has been shown to better differentiate swimmers in adjacent sport classes and reduce the within-class variability in some sport classes compared to absolute passive drag forces, thus having greater efficacy in estimating activity limitation in swimming.[9]

The results of this study contribute to the body of evidence that passive drag force normalised to body mass is an appropriate measure to estimate the activity limitation in Para swimmers with physical impairment. Despite the theoretical assumption that passive drag force is a performance-determinant only a few studies have evaluated its strength of association with swimming performance and most are limited to non-disabled participant cohorts.[8,22,25] This study found passive drag force normalised to body mass has a strong, negative correlation with 100 m freestyle race speed, explaining up to 67% of the variance in swim performance in the participant cohort using linear regression. The strength of association between passive drag and freestyle swim performance in our study is larger than a recent study that assessed Para swimmers' passive drag with arms held by their side.[8] These results confirm that passive drag should be assessed in the most streamlined body position with arms above the head for the purpose of classification to quantify the full extent of the impact that physical impairment has on swimming performance. Impairments that predispose Para swimmers to high passive drag will necessitate that they generate an equally high propulsive force, at an increasing energy cost, to maintain swim velocity.[11] However, Para swimmers with greater swim-specific impairment as described by the current classification system also tend to have lower maximum propulsive force and total metabolic energy expenditure during swimming.[7,26] Hence, the strong, negative relationship between normalised passive drag and 100 m freestyle swim performance in the participant cohort can be explained by Para swimmers with physical impairment not being able to increase propulsion or energy expenditure to overcome the high drag forces that they experience during swimming.

Passive drag was found to have a strong association with swimming performance in Para swimmers with all types of physical impairment in this study, suggesting it can provide an objective assessment of activity limitation in the entire cohort. This is unlike research that has shown active drag to be a determinant of freestyle swim performance in Para swimmers with hypertonia, ataxia, athetosis and impaired muscle power, but not Para swimmers with limb deficiency or short stature.[8] Collectively, this research confirms that passive and active drag are distinct properties that are impacted upon differently by eligible physical impairments and might both be included in classification to objectively assess activity limitation in swimming.

Despite the above, it is important that the type of physical impairment is taken into consideration when applying results of passive drag assessment in classification. This study is the first to demonstrate that the type of physical impairment affects the relationship between passive drag force and swim performance in Para swimmers. The relationship between normalised passive drag force and 100 m freestyle race speed, defined by linear regression, was most different in Para swimmers with limb deficiency compared to Para swimmers with hypertonia, ataxia, athetosis, impaired muscle power or impaired passive range of movement (Figure 2). To illustrate this difference, a Para swimmer with limb deficiency with a normalised passive drag of 0.7 $N \cdot kg^{-1}$ will be on average 9.4 seconds faster in the 100 m freestyle compared to a Para swimmer with hypertonia, ataxia or athetosis that has an equivalent normalised passive drag force. Given that different types of physical impairment are eligible to compete within the same sport class under the current World Para Swimming classification system this finding might explain, at least in part, the large variation in drag measures within sport classes.[8,9] This finding contributes to the body of evidence showing that the type of physical impairment affects the relationships between the determinants of swimming performance and suggests that it may be advantageous to classify Para swimmers into impairment-specific sport classes in which athletes will have more similar activity limitation.

The effect of type of physical impairment on the relationship between passive drag force and swimming performance might be explained by the different impact that these impairments have on the resistance components of drag. Limitations in active range of movement of the shoulder, hip, knee and ankle that affect Para swimmers with hypertonia, impaired muscle power and impaired passive range of movement might cause an increase in cross-sectional area in the direction of flow resulting in greater viscous pressure resistance at a given swim velocity.[27] This drag component would be expected to have a similar absolute contribution to total drag when swimming below and on the surface of the water assuming the projected frontal area to the flow remains unchanged.[13] In comparison, Para swimmers with short stature and limb deficiency, particularly those with bilateral upper or lower limb deficiencies, have impairments that limit their streamlined body length predisposing them to higher wave making resistance when swimming on the surface. These impairments will have less impact on total drag when gliding underwater than when swimming on the surface because of the effect of depth on wave making resistance.[13] Another explanation is that Para swimmers with certain types of physical impairment are predisposed to creating higher active drag forces.[8] Para swimmers with hypertonia, ataxia, athetosis and impaired muscle power have limitations in strength, coordination and/or active range of movement that limit their ability to minimise the disturbance of the water when swimming.[8,27-29] A greater increase in active drag relative to their passive drag, expressed as the technique effectiveness ratio or thrust deduction,[8,14] might also explain these Para swimmers having slower 100 m freestyle race speeds for a given unit of normalised passive drag force than Para swimmers with limb deficiency and short stature.

There are several limitations that should be acknowledged. There were only a small number of participants with impaired passive range of movement and short stature; these participants might not be representative of their Para swimming cohorts. The small number of participants with certain types of physical impairment also required male and female participants were pooled in our analyses. There were differences in 100 m freestyle race speed and normalised passive drag between male and female participants, and the grouping of male and female participants in linear regression might have overestimated the variance in 100 m freestyle race speed explained by the model. Sex was also found to affect the relationship between passive drag and 100 m freestyle race speed and it is possible that the relative contribution of performance determinants to swimming performance, and the relationships between passive drag force, body mass, and body shape and size (e.g. stature, frontal surface area) vary between male and female cohorts. It was not possible to obtain anthropometric measurements in all participants in this study, but further measurements might allow more appropriate normalisation of passive drag force to body shape and size.[12,30] Regardless, it is important that future research establishes the relationship between passive drag and swimming performance in an adequate sample of Para swimmers stratified by sex to account for its confounding influence on both variables. Finally, the relationships between physical impairment, passive drag and swimming performance might also be dependent on factors such as towing speed of passive drag assessment,[21] swim cap and suit worn by the swimmer during assessment,[31,32] and swim stroke and event distance.[33]

Perspective

Passive drag has been proposed as an objective measure to guide classification of Para swimmers with physical impairments,[9] although the relationship between passive drag in the most streamlined body position and swimming performance in this cohort was previously unknown. This study is the first to show normalised passive drag force explains a considerable portion of the activity limitation experienced by Para swimmers with physical impairments, confirming its usefulness as an objective measurement in Para swimming classification. However, type of physical impairment was found to affect the relationship between passive drag and 100 m freestyle swim performance; Para swimmers with certain types of physical impairment were impacted more by passive drag in the 100 m freestyle than for others. This finding contributes to the body of evidence that Para swimmers with different types of physical impairment, that compete within the same sport class in the current World Para Swimming classification system, have impairments that cause unequal or dissimilar activity limitation in swimming.[8] A classification system that allocates Para swimmers into impairment-specific sport classes might enable fairer competition by ensuring competitors within sport classes have equal and similar activity limitation in the components of a swimming race.

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Tables

Table 1. Participant characteristics, passive drag and competitive race times of Para swimmers with physical impairment.

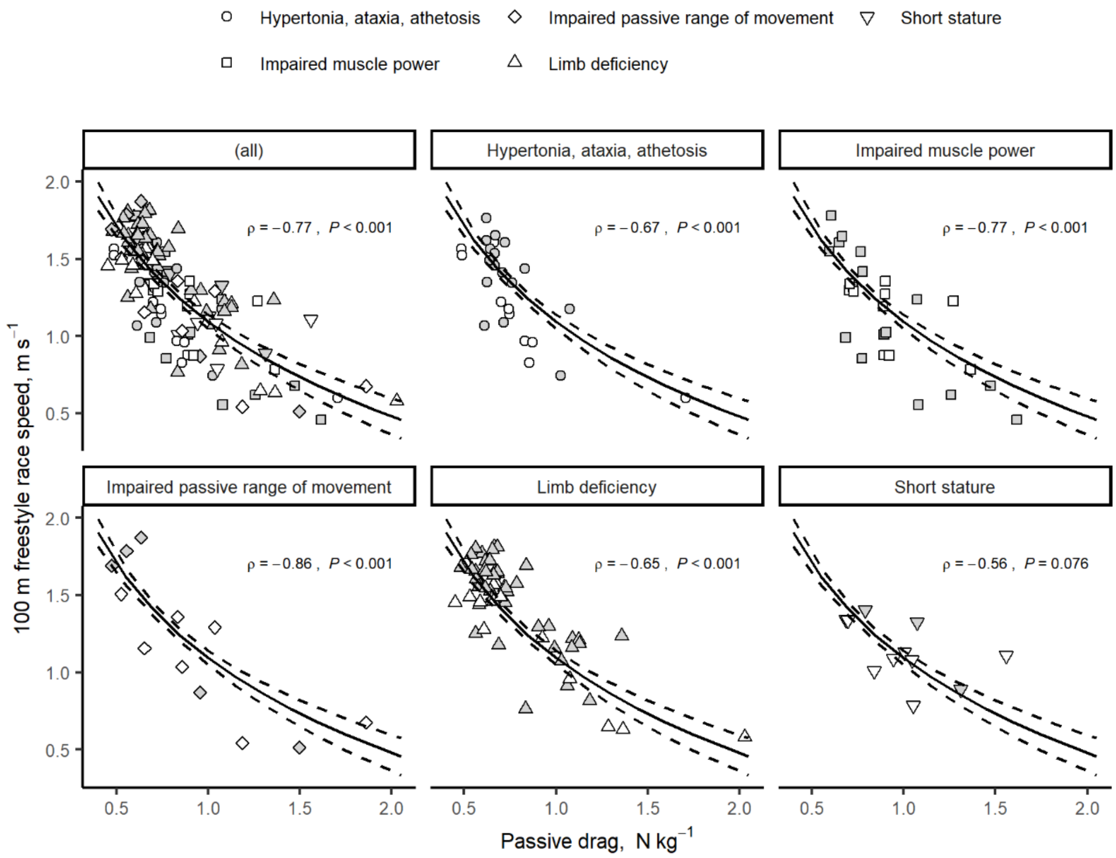
variable	Hypertonia, ataxia and athetosis	Impaired muscle power	Impaired passive range of movement	Limb deficiency	Short stature
	Men = 16	Men = 16	Men = 5	Men = 40	Men = 4
	Women = 10	Women = 10	Women = 7	Women = 17	Women = 7
Age (yrs)	23.6 ± 13.9	24.9 ± 14	21.8 ± 5.9	21.1 ± 6.7	18.5 ± 4.4
	[15.8 – 44.4]	[17.3 – 45.1]	[14.8 – 38.6]	[13.0 – 50.7]	[14.7 – 26.6]
Stature (cm)	177.3 ± 19.8	169 ± 14	165 ± 21.3	166 ± 43.2	127 ± 4
	[154 – 196.5]	[146 – 190]	[149 – 190]	[81.5 – 195]	[110 – 137.9]
Body mass (kg)	69.4 ± 19.9	60 ± 13.7	60.9 ± 23	57.8 ± 13.2	47.2 ± 7.4
	[45.9 – 91.3]	[43.2 – 78.2]	[40.3 – 90.1]	[33.2 – 90.9]	[32.2 – 56.1]
S class (S1-S10)	6 ± 2	6 ± 4	8 ± 6	9 ± 3	6 ± 0
	[3 – 10]	[1 – 10]	[3 – 10]	[2 – 10]	[3 – 6]
100 m freestyle ($m \cdot s^{-1}$)	1.35 ± 0.5	1.23 ± 0.48	1.22 ± 0.73	1.52 ± 0.43	1.11 ± 0.29
	[0.6 – 1.76]	[0.46 – 1.78]	[0.51 – 1.87]	[0.58 – 1.81]	[0.79 – 1.4]
Passive drag force (N)	47.6 ± 11	52.1 ± 14.1	52.9 ± 27.1	44.7 ± 11.2	45.1 ± 10.5
	[26.5 – 93.9]	[38.4 – 120]	[25.9 – 97.6]	[24.9 – 67.3]	[34.5 – 64.7]
Passive drag force ($N \cdot kg^{-1}$)	0.7 ± 0.17	0.89 ± 0.32	0.85 ± 0.46	0.68 ± 0.31	1 ± 0.25
	[0.49 – 1.71]	[0.59 – 1.62]	[0.47 – 1.86]	[0.45 – 2.03]	[0.69 – 1.56]
Passive drag factor ($kg \cdot m^{-1}$)	21.1 ± 5.2	23.1 ± 6.3	23.5 ± 12.1	19.9 ± 5	20 ± 4.6
	[11.8 – 41.7]	[17.1 – 53.3]	[11.5 – 43.4]	[11.1 – 29.9]	[15.3 – 28.8]
Passive drag factor (m^{-1})	0.31 ± 0.09	0.4 ± 0.14	0.38 ± 0.2	0.3 ± 0.14	0.45 ± 0.11
	[0.22 – 0.76]	[0.26 – 0.72]	[0.21 – 0.83]	[0.2 – 0.9]	[0.3 – 0.69]

Data are median ± interquartile range [range].

Figure legends

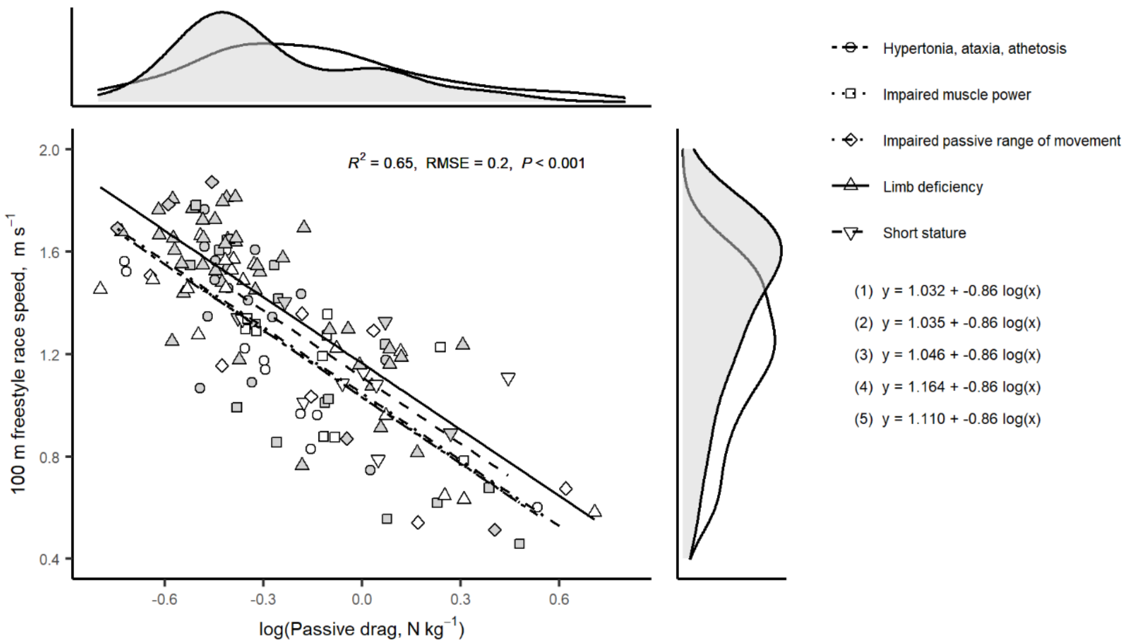
Figure 1. The association between normalised passive drag and 100 m freestyle race speed in Para swimmers with physical impairments. The points show individual cases identified by sex (male = grey, female = white) and physical impairment type. The solid black line shows the modelled relationship between normalised passive drag and 100 m freestyle race speed in the entire participant cohort. The dashed lines indicate the upper and lower 95% confidence intervals of the regression slope. Data are Spearman's rho correlation (ρ) and *p*-values (*P*).

Figure 2. Linear regression describing the relationship between the natural logarithm of normalised passive drag and 100 m freestyle race speed. The points show individual cases identified by sex (male = grey, female = white) and type of physical impairment. The lines show the modelled fit of linear regression with physical impairment type included as an effect term. Marginal plots show the distribution of 100 m freestyle race speed (right) and log-transformed normalised passive drag (top) in male (grey) and female (white) cohorts. The effect of physical impairment type on the constant (*y* intercept, b_0) is shown in equations for Para swimmers with (1) hypertonia, ataxia and athetosis, (2) impaired muscle power, (3) impaired passive range of movement, (4) limb deficiency, and (5) short stature. The type of physical impairment was not found to improve model parsimony when included in linear regression as an interaction term, and so the regression coefficient (b^1) remains unchanged between the physical impairment groups. Data are coefficient of determination (R^2), root-mean-square error (RMSE), and *p*-value (*P*).



Hypertonia, ataxia, athetosis
Impaired passive range of movement
Short stature
Impaired muscle power
Limb deficiency
(all)
Hypertonia, ataxia, athetosis
Impaired muscle power
Impaired passive range of movement
Limb deficiency
Short stature
ρ = −0.77 , P < 0.001
ρ = −0.67 , P < 0.001
ρ = −0.77 , P < 0.001
ρ = −0.86 , P < 0.001
ρ = −0.65 , P < 0.001
ρ = −0.56 , P = 0.076
100 m freestyle race speed, m s⁻¹
Passive drag, N kg⁻¹
0.5
1.0
1.5
2.0

Figure 1



Hypertonia, ataxia, athetosis
Impaired muscle power
Impaired passive range of movement
Limb deficiency
Short stature
(1) y = 1.032 + -0.86 log(x)
(2) y = 1.035 + -0.86 log(x)
(3) y = 1.046 + -0.86 log(x)
(4) y = 1.164 + -0.86 log(x)
(5) y = 1.110 + -0.86 log(x)
R2 = 0.65, RMSE = 0.2, P < 0.001
100 m freestyle race speed, m s−1
log(Passive drag, N kg−1)

Figure 2