


Please cite the Published Version

Hogarth, Luke, Payton, Carl , van de Vliet, Peter and Burkett, Brendan (2020) The impact of limb deficiency impairment on Para swimming performance. *Journal of Sports Sciences*, 38 (8). pp. 839-847. ISSN 0264-0414

DOI: <https://doi.org/10.1080/02640414.2020.1735983>

Publisher: Taylor & Francis

Version: Accepted Version

Downloaded from: <https://e-space.mmu.ac.uk/624728/>

Usage rights:  In Copyright

Additional Information: This is an Author Accepted Manuscript of an article published in *Journal of Sports Sciences* by Taylor & Francis.

Enquiries:

If you have questions about this document, contact openresearch@mmu.ac.uk. Please include the URL of the record in e-space. If you believe that your, or a third party's rights have been compromised through this document please see our Take Down policy (available from <https://www.mmu.ac.uk/library/using-the-library/policies-and-guidelines>)

The impact of limb deficiency impairment on Para swimming performance

Luke Hogarth¹, Carl Payton², Peter Van de Vliet³, Brendan Burkett¹

¹ School of Health and Sport Sciences, University of the Sunshine Coast, Sippy Downs, Australia.

² Musculoskeletal Science & Sports Medicine Research Centre, Manchester Metropolitan University, United Kingdom.

³ Medical and Scientific Department, International Paralympic Committee, Bonn, Germany.

Corresponding author:

Luke Hogarth (lhogarth@usc.edu.au)

School of Health and Sport Sciences

University of the Sunshine Coast

Australia

Abstract word count: 200

Text-only word count: 4477

Tables and figures: 5

References: 29

Acknowledgements. This work was supported by the International Paralympic Committee and UK Sport.

Abstract

Swimmers with limb deficiency are a core population within Para Swimming, accordingly this study examined the contribution of limb segments to race performance in these swimmers. Data were obtained for 174 male Para swimmers with limb deficiency. Ensemble partial least squares regression showed accurate predictions when using relative limb segment lengths to estimate Para swimmers' personal best race performances. The contribution of limb segments to performance in swim events was estimated using these regression models. The analysis found swim stroke and event distance to influence the contributions of limb segments to performance. For freestyle swim events, these changes were primarily due to the increased importance of the hand, and decreased importance of the foot and shank, as the distance of the event increased. When comparing swim strokes, higher importance of the thigh and shank in the 100 m breaststroke compared with other swim strokes confirms the separate SB class. Varied contributions of the hand, upper arm and foot suggest that freestyle could also be separated from backstroke and butterfly events to promote fairer classification. This study shows that swim stroke and event distance influence the activity limitation of Para swimmers with limb deficiency suggesting classification should account for these factors.

Keywords: Paralympic, evidence-based classification, swimming classification, physical impairment, para-sport, artificial intelligence.

Introduction

Para swimming is one of the most popular Paralympic sports that includes competitors with a wide range of physical, visual and intellectual impairments. Like all Para sports, a classification system is used in Para swimming to group athletes into classes for competition based on the activity limitation caused by their impairment. The aim of the classification system is to provide fair competition by minimising the impact that impairment has on the competition outcome (Tweedy & Vanlandewijck, 2011). This will ensure that the most successful athletes are those with the best combination of physical, technical and psychological attributes that have been gained through effective training. The effectiveness of the current Paralympic swimming classification has been questioned, leading the international federation that governs the sport to commission research that will guide a new evidence-based classification system (Burkett et al., 2018; Daly & Vanlandewijck, 1999; Wu & Williams, 1999). The most fundamental research required to guide an evidence-based classification system is the development of valid and reliable measures of impairment (Hogarth, Nicholson, et al., 2019; Hogarth, Payton, et al., 2019; Nicholson et al., 2018), and the establishment of the impact that eligible impairments have on swimming performance (Lee, Sanders, & Payton, 2014; Oh, Burkett, Osborough, Formosa, & Payton, 2013).

Para swimmers with limb deficiency have reduced limb length and surface area that affects their ability to produce propulsion and minimise their resistance in the water (Lee et al., 2014; Oh et al., 2013). The current classification system uses a points-based system to classify athletes into S (freestyle, backstroke, and butterfly), SB (breaststroke) and SM (individual medley) classes (World Para Swimming, 2017). Direct limb length measurements and body parameters are used to estimate 'healthy' limb segment lengths and determine the relative amount of limb length remaining to derive a point score that is used to assign classification. Points are assigned for the hand, forearm, upper arm, foot, shank and thigh segments, and differ for the S and SB classes based on their expected contribution to swimming performance in the different swim strokes. Although the points assigned to limb segments were derived from expert knowledge during the conception of the classification system prior to the 1992 Paralympics in Barcelona, there is little scientific evidence to substantiate whether the points weighting results in fair and equitable classification for these Para swimmers.

Recent research has aimed to establish the relationship between relative limb segment lengths and personal best 100 m freestyle performance in Para swimmers with limb deficiency (Hogarth, Payton, Van de Vliet, Connick, & Burkett, 2018). This study found ensemble partial least squares regression to provide accurate predictions of 100 m freestyle performance using limb length measures that were expressed as a percentage of the estimated 'healthy' limb segment length. Based on these predictions,

valid classification structures were derived that showed clearer and more consistent differences in 100 m freestyle performance between adjacent classes than the existing classification system does. The increased effectiveness of the newly derived classification structures was attributed to the machine learning method better accounting for the impact that limb deficiency impairment has on 100 m freestyle performance. This study and others demonstrate the potential of using data-driven machine learning techniques to establish the impact of impairment on sports performance to guide evidence-based classification in Para sport (Connick et al., 2018; Pastor, Campayo-Piernas, Pastor, & Reina, 2019).

There are several possible extensions of the above-mentioned study that can further guide evidence-based classification of Para swimmers with limb deficiency. First, the study was limited to the 100 m freestyle swim event and so did not examine the influence that swim stroke and event distance have on the relationship between limb deficiency impairment and swimming performance. The current classification system attempts to account for the influence of swim stroke by having S and SB classes, although it is unknown whether limb segments have similar contributions to swim performance in any of the swim strokes. This is a key limitation within the current system.

Research has also criticised the fact that the current classification system does not account for the influence that event distance has on the relationship between physical impairment and swimming performance (Burkett et al., 2018; Daly & Vanlandewijck, 1999). It is possible that for the same swim stroke, the contribution of limb segments to propulsion and drag forces changes with increasing event distance as do other stroke parameters, such as interlimb coordination, and the contribution of race segments to the overall outcome of a race (Cossor & Mason, 2001; Osborough, Daly, & Payton, 2015; Seifert, Chollet, & Bardy, 2004). Establishing the influence, if any, that swim stroke and event distance have on the relationship between limb deficiency impairment and swimming performance is important to guide an evidence-based classification system for Para swimmers with limb deficiency. This study aims to establish whether differences exist in the contribution of limb segments to race performance in swim events stratified by stroke and event distance.

Methods

Design

Data for 174 male Para swimmers with limb deficiency were obtained from athlete classification records listed in the International Paralympic Committee (IPC) Sports Data Management System (SDMS). Para swimmers were included in analyses if they had received international classification and

were listed as being 'active' at the time of data collection. Para swimmers were removed from analysis if they had a secondary impairment other than limb deficiency and did not have a recorded race time for a long course event in at least one of the swim events included in analysis. The swim events included in analysis were the 50 m freestyle, 100 m freestyle, 400 m freestyle, 100 m backstroke, 100 m butterfly and 100 m breaststroke. These events were chosen to allow for a novel analysis on the influence of swim stroke and event distance on the relationship between limb deficiency and swimming performance. Data were collected under approved ethical guidelines from the institution's Human Research Ethics Committee.

Data

All data were obtained from athlete classification records listed on the IPC SDMS until the end of the 2016 calendar year (Hogarth et al., 2018). Personal best race times for swim events were recorded and expressed as mean race swim speed (m/s). Race times for short course events were excluded to remove any possible influence of varied contributions of start and turn components to overall race performance. Para swimmers were classified as international standard if they had previously competed at a Paralympic or World Championship event (n = 93, 53%). All other swimmers were classified as national standard (n = 81, 47%). Absolute limb length measures for the hand, forearm, upper arm, foot, shank and thigh were obtained from Para swimmers' classification records and converted to relative limb length measures for analysis (World Para Swimming, 2017; Hogarth, Payton, et al., 2019). The method for obtaining absolute and relative limb segment lengths has been detailed previously (Hogarth, Payton, et al., 2019). In addition to Para swimming performances, the recorded race times for able-bodied swimmers in the semi-finals of corresponding events during the 2015 World Championships were obtained (www.omegatiming.com). Able-bodied swimming performances were included in analyses by assigning relative limb segment lengths to cases (i.e. 100%).

Statistical analysis

Statistics were performed using R version 3.4.1 (R Core Team, 2017). The relationship between limb deficiency impairment, described by remaining limb segment lengths, and performance in each swim event was established using ensemble partial least squares regression. The partial least squares method is a dimension reduction technique that transforms independent and dependent variables into x- and y-components. The advantage of this method is that while the independent variables may be collinear the derived x-components used in regression will be independent of one another (Mevik & Wehrens, 2007). The ensemble learning method is also advantageous as it exploits the distribution in prediction errors and regression coefficients within a dataset to improve prediction accuracy and stability of regression (Cao et al., 2017).

A systematic approach was used to train and test ensemble partial least squares regression. The entire cohort of swimmers with a recorded race time for the event being analysed was included in ensemble partial least squares regression. A sampling ratio of 0.8 was used for 100 Monte Carlo experiments and K-fold cross validation was used to evaluate prediction accuracy, error and stability of ensemble partial least squares regression. Outlying cases in the dataset were then identified and removed based on the mean absolute error and standard deviation of absolute error for each case (Cao et al., 2017). This was undertaken as it was expected that not all swimmers with a recorded race time for the event of interest were specialists in that event and the removal of outliers was considered the best approach to derive a substantial and representative sample of swimmers for model training. After obtaining a clean data set, ensemble partial least squares regression was retrained to establish the relationship between limb segment lengths and competitive swim performance, with stability of regression being reconfirmed using K-fold cross validation. This analysis was conducted twice for each swim event, once including the entire cohort of Para swimmers, and once including only Para swimmers of international standard.

The swim performance of all Para swimmers was estimated using the trained ensemble partial least squares regression with the highest prediction accuracy and stability. In all cases this was the model trained using only international Para swimmers. Kendall's tau coefficient was calculated to determine the strength of association between predicted swim performances among swim events. A higher tau coefficient indicates that the swim events are influenced similarly by the location and severity of limb deficiency as opposed to a lower tau coefficient.

The activity limitation resulting from hypothetical cases of limb deficiency (e.g. single through wrist impairment) that explain the contribution of whole limb segments to swim performance was estimated using the ensemble partial least squares regression with the highest prediction accuracy and stability for each event. For each case, the partial least squares regressions trained using 100 Monte Carlo experiments returned a predicted value of swim performance (i.e. there were 100 predicted values returned for each case of limb deficiency for each event). The limb segment contribution to swim performance derived was then shown by calculating the difference in predicted values among hypothetical cases of limb deficiency (i.e. the contribution of the forearm segment was calculated by the predicted performance of a single through wrist impairment minus the predicted performance of a single through elbow impairment). This allowed for a novel analysis on limb segment contribution to swim events that accounted for the uncertainty of predictions derived from ensemble partial least squares regression. Kruskal-Wallis and Wilcoxon rank tests were used to determine differences in limb segment contributions between swim events of different swim stroke (100 m

freestyle, 100 m breaststroke, 100 m butterfly, and 100 m backstroke) and event distance (50 m freestyle, 100 m freestyle, and 400 m freestyle).

Results

Ensemble partial least squares regression models explained between 48% and 87% of the variance in personal best performance in swim events (Table 1). Prediction and residual plots for partial least squares regressions trained in the entire cohort of Para swimmers and international-level Para swimmers only are shown in the Supplementary Appendix. The highest prediction accuracy was found for models trained for the 50 m freestyle ($R^2 = .72-.86$, RMSE = .12-.14) and 100 m freestyle swim events ($R^2 = .70-.87$, RMSE = .12-.15). The ensemble partial least squares regressions trained for the 400 m freestyle event had similar or lower mean prediction error than other events, although tended to explain less variance in personal best performance ($R^2 = .50-.73$, RMSE = .10-.14). Although marginal, prediction accuracy was lower, and prediction error greater, for the 100 m backstroke ($R^2 = .57-.78$, RMSE = .13-.16) and 100 m breaststroke swim events ($R^2 = .48-.78$, RMSE = .12-.19). There were higher prediction accuracies and stability for all models that were trained with Para swimmers of international standard ($R^2 = 0.73$ to 0.87 and $cvR^2 = 0.70$ to 0.85) compared with models that were trained in the entire cohort of Para swimmers ($R^2 = 0.48$ to 0.73 and $cvR^2 = 0.44$ to 0.72).

The association between predicted performances among different swim events are shown in Figure 1. Kendall's Tau correlations showed the most similar predicted performances for Para swimmers in the 100 m butterfly and 100 m backstroke swim events, showing an almost perfect correlation ($\tau = 0.97$). When considering the influence of swim stroke the most dissimilar predicted performances between swim events were found when comparing the 100 m breaststroke with the 100 m backstroke ($\tau = 0.82$) and 100 m butterfly ($\tau = 0.80$). The lowest correlation between predicted swim performances between swim events that are undertaken within the same sport class was found for the 50 m freestyle and 400 m freestyle ($\tau = 0.77$).

There were changes in the rank order of predicted performances for hypothetical cases of limb deficiency between swim events of different swim stroke and event distance (Figure 2). Although the rank order of hypothetical cases of limb deficiency remained unchanged for the 100 m backstroke and 100 m butterfly, there were differences when comparing these events to both the 100 m freestyle and 100 m breaststroke. These changes are explained by differences in the contribution of the thigh and shank in the 100 m breaststroke, and the contribution of the hand, forearm and upper arm in the 100 m freestyle compared with the other swim events (Figure 3). There were also changes in the rank

order of Para swimmers with a single upper or lower limb impairment in freestyle events (Figure 2) that was evidenced by higher contribution of the hand, and lower contributions of the foot and shank, with increasing event distance (Figure 4).

Discussion

This study established the contribution of limb segments to Para swimming performance to provide evidence for the classification of swimmers with limb deficiency. Based on the results of ensemble partial least squares regression, the activity limitation resulting from Para swimmers' limb deficiency impairments was estimated. This knowledge can then determine which swim events, if any, had dissimilar relationships between limb deficiency impairment and performance that would warrant the allocation of separate sport classes. It was found that swim stroke and event distance influence the contribution of limb segments to swim performance to the extent that the current classification system might not be fit-for-purpose.

The variance in swim performance explained by measures of physical impairment in this study is similar to previous research (Hogarth, Payton, et al., 2019; Hogarth et al., 2018). Ensemble partial least squares regression explained between 47% and 87% of the variance in personal best swim performances from limb segment length measures. The inclusion of data for able-bodied swimmers in this study resulted in limb segment length measures explaining a further 7% variance in personal best 100 m freestyle performance than for previous research (Hogarth et al., 2018). This highlights that the variance of sports performance explained by impairment measures is dependent on the range of activity limitation (i.e. impairment severity) that is present within the participant cohort. Data for able-bodied swimmers were included in this study as it was thought the minimum eligibility criteria would influence the defined relationship between distal limb segment lengths and swimming performance. For example, previously it was estimated that the forearm (7.6%) had a greater contribution to 100 m freestyle performance compared with the hand (6.2%), while the results of this study suggest that the hand segment has higher importance than first estimated (7.3%). Although only a marginal difference, these results suggest that it is good practice to include data for able-bodied athletes in predictive models when estimating the impact of physical impairment on sports performance.

There were considerably higher prediction accuracies found for ensemble partial least squares regressions that were trained with international Para swimmers only than for the entire Para swimming cohort (Table 1). The cohort of international Para swimmers would have optimised their

anthropometrical, biomechanical, physiological and psychological determinants of performance to greater effect than national Para swimmers, and so the variance in swim performance in this cohort is more likely to be explained by measures of limb deficiency impairment than other confounding variables. The differences in prediction accuracies were also larger for the 100 m backstroke, 100 m breaststroke, 100 m butterfly and 400 m freestyle. These are specialist swim events that might involve more complex coordination patterns and require greater technical skill development than the 50 m and 100 m Freestyle (Barbosa, Goh, Morais, & Costa, 2017; Bartolomeu, Costa, & Barbosa, 2018). The influence of training status on the certainty of the established relationships between physical impairment and sports performance suggests researchers should consider limiting their participant cohort to highly trained, specialist athletes where possible.

In agreement with the current classification system, Para swimmers showed the most dissimilar predicted performances among swim events for the 100 m breaststroke (Figure 1). This can mostly be attributed to the increased importance of the thigh and shank segments to performance in the 100 m breaststroke compared with other swim events (Figure 3). Previous research has shown higher relative swim velocities using the arm-stroke only (79 to 90%) compared with leg kicking only (57 to 73%) in front crawl, backstroke and butterfly in able-bodied swimmers suggesting that the upper limbs have a greater overall importance to swim performance in these strokes compared with the lower limbs (Bartolomeu et al., 2018). Comparatively, swimmers produce similar or higher swim speed when leg kicking only compared with arm-stroke only in the breaststroke (Bartolomeu et al., 2018). The reason for the increased importance of the lower limbs in breaststroke is that the orientation of the lower limb segments and their horizontal action during the breaststroke kick creates greater propulsion to overcome drag forces, as opposed to other strokes where the orientation of leg kicking is mostly vertical (Vorontsov & Rumyantsev, 2000a).

There were more similar limb segment contributions found for the swim events that make up the S sport class. The predicted performances of Para swimmers for the 100 m butterfly and 100 m backstroke showed an almost perfect correlation ($\tau = 0.97$), with the hand, thigh and foot segments having the highest contributions to swim performance in both events (Figure 3). Still, there were differences found in the contribution of most limb segments to performance in these events, particularly the forearm segment, that could impact on fairness of classification for Para swimmers with an impairment above the wrist joint (Figure 2). There were more apparent differences in limb segment contributions found when comparing the 100 m freestyle to the 100 m backstroke and butterfly events (Figure 1 and Figure 3). The differences in limb segment contributions is enough to change the rank order of predicted performance for some limb deficiency profiles, particularly those athletes with a single below elbow or single below knee impairment (Figure 2). The results of this study

can be used to determine classification for each swim stroke to best promote fairness for all athletes with limb deficiency, rather than grouping swim strokes into any single sport class.

The aggregated contribution of the upper and lower limb segments to swim performance in the 100 m freestyle, backstroke and butterfly events is inconsistent with some research. Studies have shown able-bodied swimmers to produce larger propulsive force and swim velocities when performing arms-only compared with legs-only swimming (Bartolomeu et al., 2018; Morouco, Marinho, Izquierdo, Neiva, & Marques, 2015). In front crawl for example, the difference in relative swim velocity attained using arms-only (86% of full-stroke) and legs-only (59% of full-stroke) swimming has been as large as 27% of swimmers' full-stroke swim velocities (Bartolomeu et al., 2018). Similar differences have been shown between the propulsive forces produced during arms-only and legs-only tethered swimming (Morouco et al., 2015). However, when aggregating the median estimate of contribution of limb segments this study found the lower limbs to have greater contribution to swim performance in all swim events, except for the 400 m freestyle (Figure 3 and Figure 4). For instance, the ratios of lower to upper limb segment contributions ranged between 1.02 to 1.13 for the 100 m freestyle, butterfly and backstroke events (i.e. the lower limb has 1.13 times more contribution to swim performance than the upper limb). This difference is marginal, albeit unexpected given the research showing the greater swim velocities and propulsive forces attained using arms-only versus legs-only swimming.

These results can be explained by the impact that lower limb loss might have on swimmers' drag profiles as well as the impaired ability to facilitate the propulsive actions of the arm pull by using an effective leg kick. In swimming strokes with alternative arm and leg movements it is necessary to avoid significant deviation of hydrodynamic reaction forces from the swimming direction, as this causes undesired vertical and transverse movement increasing hydrodynamic drag force (Vorontsov & Rumyantsev, 2000b). Several limb segments contribute to drag and lift forces that serve to balance the vertical and transverse forces of pulling movements so that body alignment is maintained, and hydrodynamic drag force minimised (Vorontsov & Rumyantsev, 2000a). This is evidenced by the contributions of the lower limb segments to swim performance in freestyle and backstroke (Figure 3). These segments may be most important to performance in these strokes for their compensatory actions.

Interestingly, there were similar or higher correlations found for predicted performances between the 100 m freestyle, butterfly and backstroke events ($\tau = 0.88$ to 0.90), than for the 50 m, 100 m and 400 m freestyle ($\tau = 0.77$ to 0.87). These results suggest that event distance has more influence on the relationship between limb deficiency impairment and swim performance than for swim stroke in these events comprising the S sport class. The interaction between limb segments and the water, such as

drag and lift forces, might change with increasing swim distance as do other parameters including stroke rate, stroke length, intra-cyclic velocity fluctuation, and interlimb coordination (Osborough et al., 2015; Osborough, Payton, & Daly, 2010; Pelayo, Alberty, Sidney, Potdevin, & Dekerle, 2007; Seifert et al., 2004). As increased stroke efficiency is required with longer race distance, the lower limb segments may play less of a role in generating propulsion and better serve by performing their compensatory actions. Conversely, with shorter race distances an increased leg kicking amplitude might allow for the lower limb segments that are the main propelling segments of the lower leg, the foot and distal half of the shank, to have a greater contribution to propulsion and swim velocity.

This is contradictory of previous research that has used computational fluid dynamics to estimate the forces of the upper and lower limbs to propulsion during front crawl swimming at different stroke rates (Cohen, Cleary, Mason, & Pease, 2018). This research found that with increasing stroke rates and swimming speeds, the lower limbs generate relatively less thrust than the upper limbs due to the increased hydrodynamic drag force at higher swim speeds, even with higher kick frequencies. In fact, they found the ratio of thrust from upper to lower limbs increased from 1.1 to 2.5 with increasing stroke rates and swim speed. The results of this study are contradictory to this research, showing the lower limb segments that are the major contributors of the lower limb to propulsion, the foot and shank, to have increased importance to freestyle swimming in the short distance events.

There are several explanations for this finding. First, although the shank and foot segments might contribute little propulsion to the direction of swimming, their coordination with the upper limbs facilitate the pulling actions of the upper limb while minimising hydrodynamic drag force. Due to increasing energetic demand high stroke rates and kicking frequencies are less economical with increasing event distance (Pyne & Sharp, 2014). For longer distance events, the orientation of the thigh segment might serve to counteract the pulling actions of the upper limb without the need for increased vertical or transverse forces generated by the shank and foot segments. Second, it is important to consider how the interactions between propulsion generated by the upper and lower limbs and swim velocity could change for Para swimmers with limb deficiency (Lecrivain, Payton, Slaouti, & Kennedy, 2010; Lecrivain, Slaouti, Payton, & Kennedy, 2008). The non-linear properties of upper and lower limb actions during the swim strokes (Bartolomeu et al., 2018), and altered arm and leg coordination of Para swimmers with limb deficiency (Osborough et al., 2015; Osborough et al., 2010) show that Para swimmers can use altered kick-to-stroke rates and amplitudes to manipulate the relative contributions of the upper and lower limbs (Fulton, Pyne, & Burkett, 2011).

This study provides new knowledge to guide classification of Para swimmers with limb deficiency although it is not comprehensive. Only male swimmers were included in the analysis limiting the

transference of results to classification of female Para swimmers. Although it is unlikely that the impact of limb deficiency impairment is influenced markedly by gender it is important that future studies establish that this is the case. This study also limited the measures used to describe the location and distribution of limb deficiency. The relative limb length measures used in this study are equivalent to those used by the current classification system. However, it is possible that the inclusion of measures such as streamline height and limb length symmetry further explain activity limitation in Para swimmers with limb deficiency. Further research is required to identify measures that describe the location, distribution and severity of limb deficiency and establish the strength of association between these measures and swim performance. Estimates of limb segment contributions to swim performance might also change markedly for Para swimmers with dysmelia whose proximal rather than distal limb segments are affected by their medical conditions. It is important that studies establish the effect that specific cases of limb deficiency impairment have on the biomechanical determinants of swim performance to guide classification in these cases. Finally, the impairment-performance relationships that have been established in this study are dependent upon the training status and event specialisation of Para swimmers that have been included in analysis. Although steps have been taken to reduce this bias it should be noted that varying relationships may be established in other participant cohorts, or within the same participant cohort at different times, when interpreting the results of this study.

Conclusion

This study found both swim stroke and event distance influence the relationship between limb deficiency impairment and swim performance. The varied contributions of limb segments to performance in swim events causes considerable differences in the ranking of limb deficiency profiles. This suggests that Para swimming classification should account for the influence of swim stroke and event distance on the activity limitation experienced by Para swimmers with limb deficiency. The models trained in this study that showed accurate and stable predictions can be used to estimate the activity limitation of Para swimmers with limb deficiency to guide their classification.

Tables and Figures

Table 1. Prediction accuracy, error and internal cross-validation of ensemble partial least squares regression in predicting personal best race performances from relative limb segment lengths.

				Personal best race performance (m/s)	Ensemble PLSR		K-fold cross validation	
		n	Sport class	Median (range)	R ²	RMSE	R ²	RMSE
50 m freestyle	Entire cohort	154	S4 to s10	1.68 (1.06 to 2.01)	0.72	0.14	0.71	0.14
	International	82	S4 to s10	1.80 (1.06 to 2.01)	0.86	0.12	0.84	0.12
100 m freestyle	Entire cohort	157	S4 to s10	1.51 (0.61 to 1.84)	0.70	0.15	0.69	0.15
	International	86	S4 to s10	1.57 (0.76 to 1.84)	0.87	0.12	0.86	0.12
400 m freestyle	Entire cohort	105	S5 to S10	1.37 (0.89 to 1.63)	0.50	0.14	0.45	0.14
	International	62	S5 to S10	1.40 (1.05 to 1.63)	0.73	0.10	0.70	0.10
100 m breaststroke	Entire cohort	127	SB4 to SB9	1.12 (0.48 to 1.49)	0.48	0.19	0.42	0.20
	International	58	SB4 to SB9	1.22 (0.59 to 1.49)	0.78	0.12	0.74	0.13
100 m backstroke	Entire cohort	122	S4 to s10	1.36 (0.75 to 1.72)	0.57	0.16	0.54	0.17
	International	71	S4 to s10	1.38 (0.84 to 1.72)	0.78	0.13	0.73	0.14
100 m butterfly	Entire cohort	93	S5 to S10	1.49 (0.78 to 1.72)	0.63	0.15	0.59	0.16
	International	56	S5 to S10	1.53 (0.89 to 1.72)	0.81	0.11	0.78	0.12

PLSR = Partial least squares regression. R² = coefficient of determination. RMSE = Root mean square error.

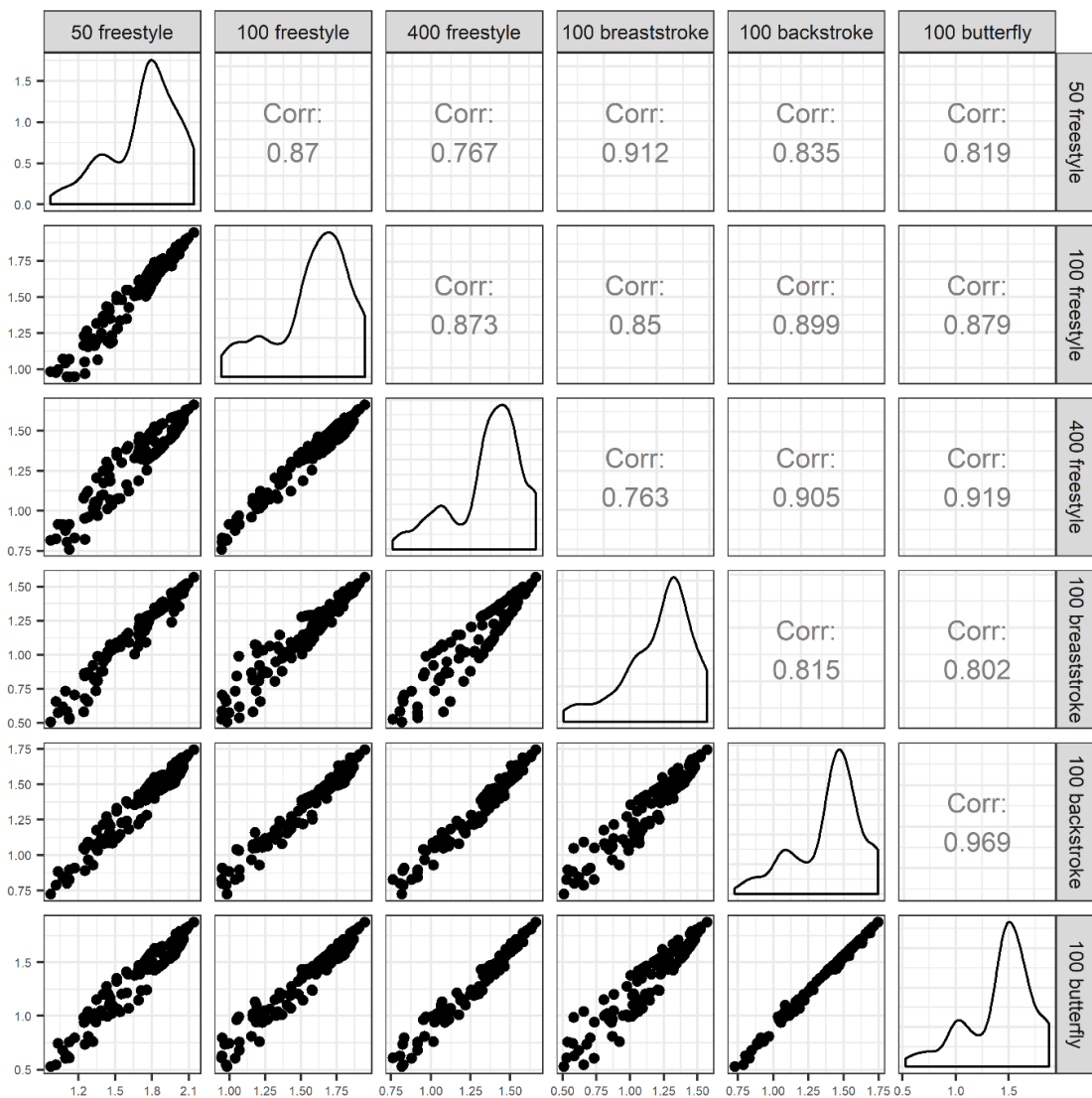


Figure 1. Scatterplot matrix showing the similarities in activity limitation experienced by Para swimmers with limb deficiency in different swim events. Data are Kendall's Tau with values closer to 1 indicating larger rank correlations between predicted swim performances.

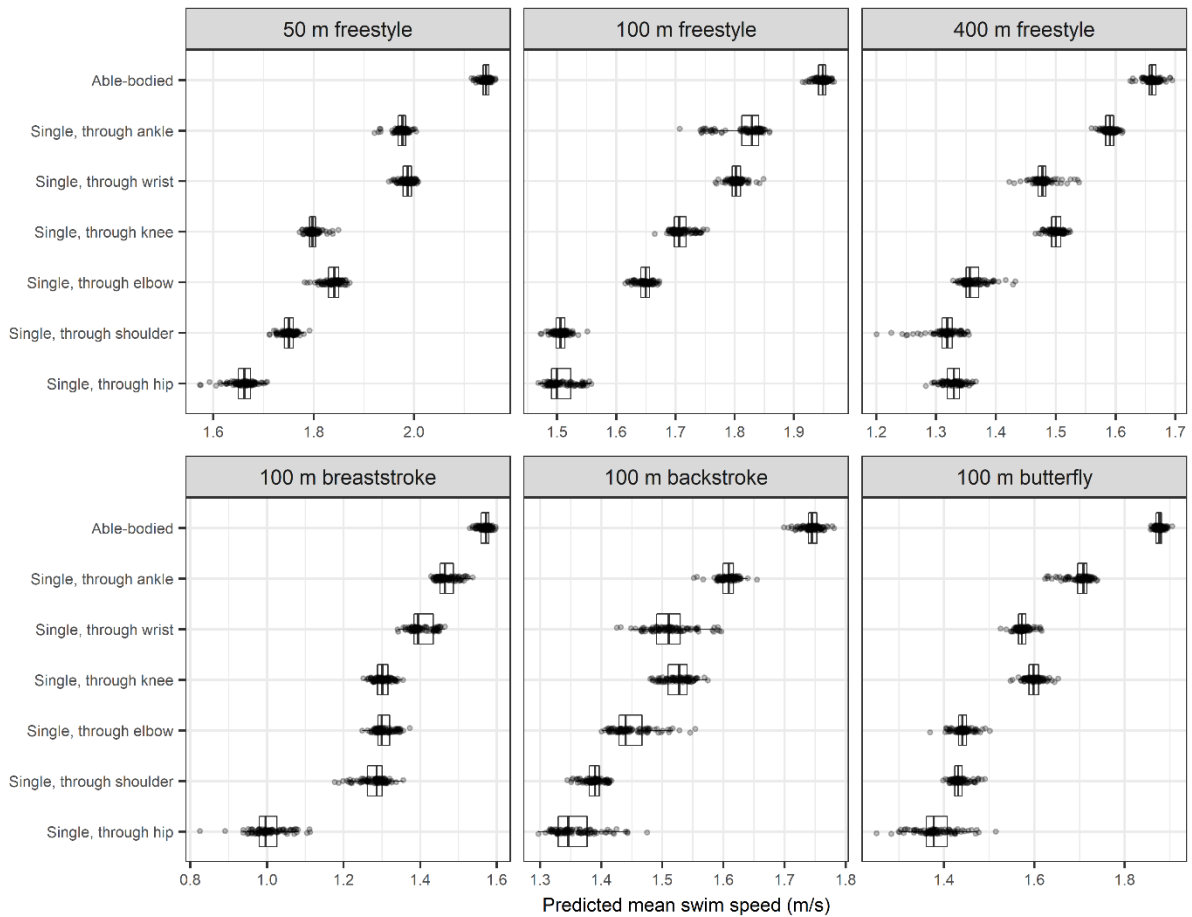


Figure 2. Estimated activity limitation of limb deficiency impairment profiles for swim events. Predicted performances are derived from ensemble partial least squares regression trained with data for international Para swimmers only. There were significant differences between all hypothetical cases of limb deficiency except for: Single, through shoulder and single, through hip impairments in the 100 m freestyle ($p=0.35$); and single, through elbow and single, through knee impairments in the 100 m ($p=0.45$).

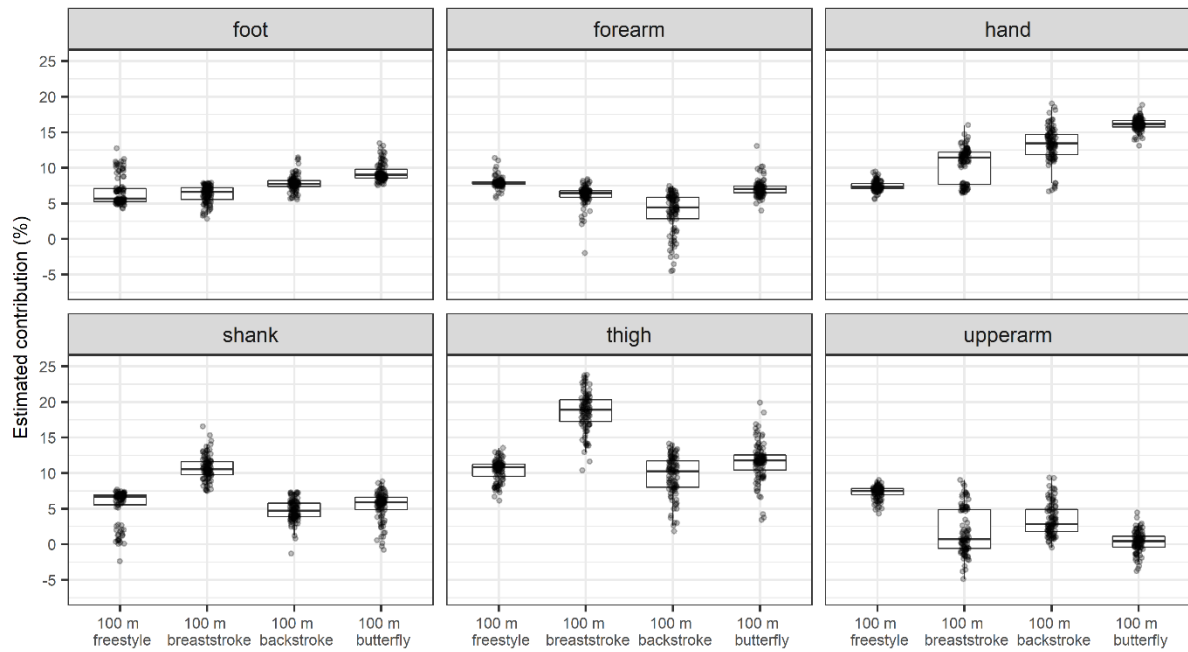


Figure 3. Estimated contribution of limb segment lengths to performance in swim events of different swim strokes. Data are based on differences in predicted performance for limb deficiency impairment profiles (see Figure 2) and are expressed as a percentage of predicted performances of an able-bodied swimmer. There were significant differences in limb segment contributions between all events, except for: The foot for the 100 m freestyle and 100 m breaststroke ($p=0.99$); and the thigh for the 100 m freestyle and 100 m backstroke ($p=0.42$).

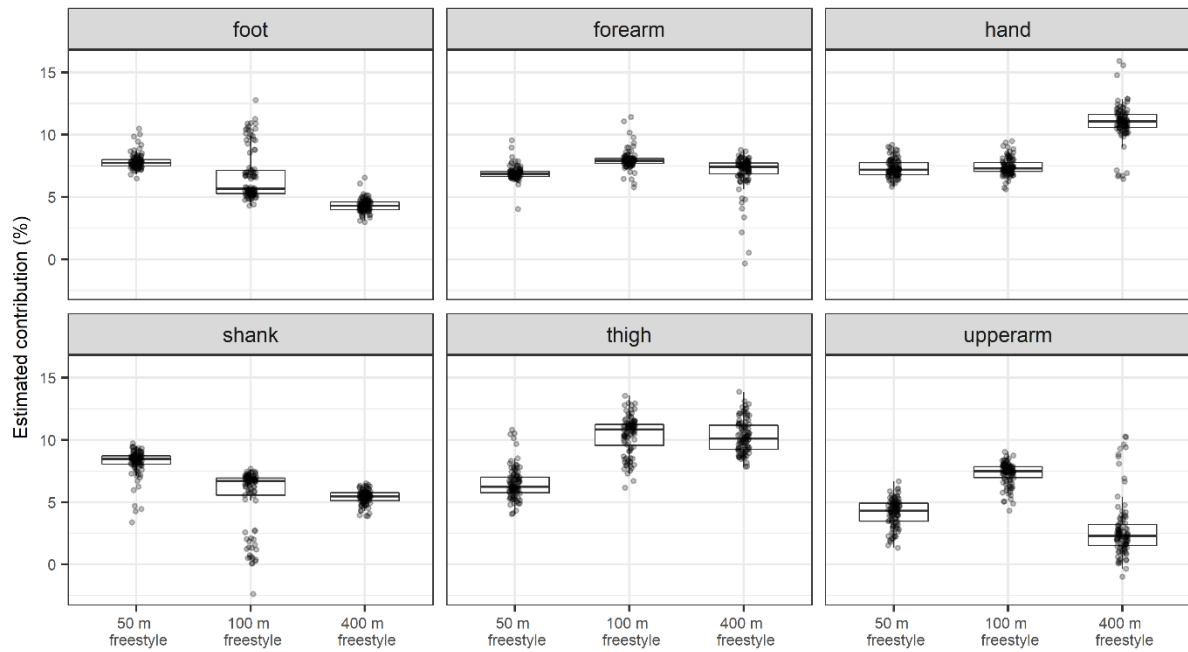


Figure 4. Estimated contribution of limb segment lengths to performance in freestyle swim events of different event distance. Data are based on differences in predicted performance for limb deficiency impairment profiles (see Figure 2) and are expressed as a percentage of predicted performances of an able-bodied swimmer. There were significant differences in limb segment contributions between all events, except for: The hand for the 50 m freestyle and 100 m freestyle ($p=0.29$); and the thigh for the 100 m freestyle and 400 m freestyle ($p=0.42$).

References

- Barbosa, T. M., Goh, W. X., Morais, J. E., & Costa, M. J. (2017). Variation of linear and nonlinear parameters in the swim strokes according to the level of expertise. *Motor Control*, 21(3), 312-326. doi: 10.1123/mc.2015-0097
- Bartolomeu, R. F., Costa, M. J., & Barbosa, T. M. (2018). Contribution of limbs' actions to the four competitive swimming strokes: a nonlinear approach. *J Sports Sci*, 36(16), 1836-1845. doi: 10.1080/02640414.2018.1423608
- Burkett, B., Payton, C., Van de Vliet, P., Jarvis, H., Daly, D., Mehrkuehler, C., . . . Hogarth, L. (2018). Performance characteristics of Para swimmers: How effective is the swimming classification system? *Phys Med Rehabil Clin N Am*, 29(2), 333-346. doi: 10.1016/j.pmr.2018.01.011
- Cao, D. S., Deng, Z. K., Zhu, M. F., Yao, Z. J., Dong, J., & Zhao, R. G. (2017). Ensemble partial least squares regression for descriptor selection, outlier detection, applicability domain assessment, and ensemble modeling in QSAR/QSPR modeling. *J Chemom*, 31(11), e2922. doi: ARTN e292210.1002/cem.2922
- Cohen, R. C. Z., Cleary, P. W., Mason, B. R., & Pease, D. L. (2018). Forces during front crawl swimming at different stroke rates. *Sports Eng*, 21(1), 63-73. doi: 10.1007/s12283-017-0246-x
- Connick, M. J., Beckman, E., Vanlandewijck, Y., Malone, L. A., Blomqvist, S., & Tweedy, S. M. (2018). Cluster analysis of novel isometric strength measures produces a valid and evidence-based classification structure for wheelchair track racing. *Br J Sports Med*, 52(17), 1123-1129. doi: 10.1136/bjsports-2017-097558
- Cossor, J. M., & Mason, B. (2001). Swim start performances at the Sydney 2000 Olympic Games. Proceedings of XIX Symposium on Biomechanics in Sport, San Francisco, 70-74.
- Daly, D. J., & Vanlandewijck, Y. (1999). Some criteria for evaluating the "fairness" of swimming classification. *Adapt Phys Act Q*, 16(3), 271-289. doi: 10.1123/apaq.16.3.271
- Fulton, S. K., Pyne, D., & Burkett, B. (2011). Optimizing kick rate and amplitude for Paralympic swimmers via net force measures. *J Sports Sci*, 29(4), 381-387. doi: 10.1080/02640414.2010.536247
- Hogarth, L., Nicholson, V., Spathis, J., Tweedy, S., Beckman, E., Connick, M., . . . Burkett, B. (2019). A battery of strength tests for evidence-based classification in Para swimming. *Journal of Sports Sciences*, 37(4), 404-413. doi: 10.1080/02640414.2018.1504606
- Hogarth, L., Payton, C., Nicholson, V., Spathis, J., Tweedy, S., Connick, M., . . . Burkett, B. (2019). Classifying motor coordination impairment in Para swimmers with brain injury. *J Sci Med Sport*, 22(5), 526-531. doi: 10.1016/j.jsams.2018.11.015
- Hogarth, L., Payton, C., Van de Vliet, P., Connick, M., & Burkett, B. (2018). A novel method to guide classification of para swimmers with limb deficiency. *Scand J Med Sci Sports*, 28(11), 2397-2406. doi: 10.1111/sms.13229
- Lecrivain, G., Payton, C., Slaouti, A., & Kennedy, I. (2010). Effect of body roll amplitude and arm rotation speed on propulsion of arm amputee swimmers. *J Biomech*, 43(6), 1111-1117. doi: 10.1016/j.jbiomech.2009.12.014
- Lecrivain, G., Slaouti, A., Payton, C., & Kennedy, I. (2008). Using reverse engineering and computational fluid dynamics to investigate a lower arm amputee swimmer's performance. *J Biomech*, 41(13), 2855-2859. doi: 10.1016/j.jbiomech.2008.06.036
- Lee, C. J., Sanders, R. H., & Payton, C. J. (2014). Changes in force production and stroke parameters of trained able-bodied and unilateral arm-amputee female swimmers during a 30 s tethered front-crawl swim. *J Sports Sci*, 32(18), 1704-1711. doi: 10.1080/02640414.2014.915420
- Mevik, B. H., & Wehrens, R. (2007). The pls package: Principal component and partial least squares regression in R. *Journal of Statistical Software*, 18(2), 1-23
- Morouco, P. G., Marinho, D. A., Izquierdo, M., Neiva, H., & Marques, M. C. (2015). Relative contribution of arms and legs in 30 s fully tethered front crawl swimming. *Biomed Res Int*, 2015, 563206. doi: 10.1155/2015/563206

- Nicholson, V. P., Spathis, J. G., Hogarth, L. W., Connick, M. J., Beckman, E. M., Tweedy, S. M., . . . Burkett, B. J. (2018). Establishing the reliability of a novel battery of range of motion tests to enable evidence-based classification in Para Swimming. *Phys Ther Sport*, 32, 34-41. doi: 10.1016/j.ptsp.2018.04.021
- Oh, Y. T., Burkett, B., Osborough, C., Formosa, D., & Payton, C. (2013). London 2012 Paralympic swimming: passive drag and the classification system. *Br J Sports Med*, 47(13), 838-843. doi: 10.1136/bjsports-2013-092192
- Osborough, C., Daly, D., & Payton, C. (2015). Effect of swim speed on leg-to-arm coordination in unilateral arm amputee front crawl swimmers. *J Sports Sci*, 33(14), 1523-1531. doi: 10.1080/02640414.2014.996181
- Osborough, C. D., Payton, C. J., & Daly, D. J. (2010). Influence of swimming speed on inter-arm coordination in competitive unilateral arm amputee front crawl swimmers. *Hum Mov Sci*, 29(6), 921-931. doi: 10.1016/j.humov.2010.05.009
- Pastor, D., Campayo-Piernas, M., Pastor, J. T., & Reina, R. (2019). A mathematical model for decision-making in the classification of para-footballers with different severity of coordination impairments. *J Sports Sci*, 37(12), 1403-1410. doi: 10.1080/02640414.2018.1560617
- Pelayo, P., Alberty, M., Sidney, M., Potdevin, F., & Dekerle, J. (2007). Aerobic potential, stroke parameters, and coordination in swimming front-crawl performance. *Int J Sports Physiol Perform*, 2(4), 347-359. doi: 10.1123/ijsp.2.4.347
- Pyne, D. B., & Sharp, R. L. (2014). Physical and energy requirements of competitive swimming events. *Int J Sport Nutr Exerc Metab*, 24(4), 351-359. doi: 10.1123/ijsnem.2014-0047
- Seifert, L., Chollet, D., & Bardy, B. G. (2004). Effect of swimming velocity on arm coordination in the front crawl: a dynamic analysis. *J Sports Sci*, 22(7), 651-660. doi: 10.1080/02640410310001655787
- Tweedy, S. M., & Vanlandewijck, Y. C. (2011). International Paralympic Committee position stand--background and scientific principles of classification in Paralympic sport. *Br J Sports Med*, 45(4), 259-269. doi: 10.1136/bjism.2009.065060
- Vorontsov, A. R., & Romyantsev, V. A. (2000a). Propulsive Forces in Swimming *Biomechanics in Sport* (pp. 205-231): Blackwell Science Ltd.
- Vorontsov, A. R., & Romyantsev, V. A. (2000b). Resistive Forces in Swimming *Biomechanics in Sport* (pp. 184-204): Blackwell Science Ltd.
- World Para Swimming. (2017). *World Para Swimming Classification Rules and Regulations*: International Paralympic Committee.
- Wu, S. K., & Williams, T. (1999). Paralympic swimming performance, impairment, and the functional classification system. *Adapt Phys Act Q*, 16(3), 251-270. doi: 10.1123/apaq.16.3.251