Modelling the age-related trajectory of performance in Para swimmers with physical, vision and intellectual impairment

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Abstract

This study is the first to provide information on the age-related trajectories of performance in Para swimmers with physical, vision and intellectual impairment. Race times from long-course swim meets between 2009 and 2019 were obtained for Para swimmers with an eligible impairment. A subset of 10661 times from 411 Para swimmers were included in linear mixed effects modelling to establish the relationship between age and performance expressed relative to personal best time and world record time. The main findings were: (i) age has the most noticeable influence on performance between the ages of 12-20 years before performances stabilise and peak in the early- to late-twenties, (ii) women have faster times relative to personal best and world record time than men during early adolescence and their performances stabilise, peak and decline at younger ages, and (iii) Para swimmers from different sport classes show varying age-related trajectories in performance after maturation and when training-related factors are more likely to explain competitive swim performance. The results of this study can guide talent identification and development of Para swimmers at various stages of their career and help to inform decision-making on the allocation of sport class and sport class status in Para swimming classification.

Keywords: Paralympic, evidence-based classification, Para sport, talent identification, athlete development, swimming.

Introduction

A key difference between Olympic and Paralympic sport is the use of international classification systems to determine athlete eligibility and the grouping of athletes for competition. Classification systems play an integral role in Paralympic sport and aim to promote increased participation by people with disabilities by minimising the impact that impairment has on the competition outcome.[1] Para swimming, one of the most popular Paralympic sports, comprises sport classes based on physical, vision and intellectual impairments.[2] The international Para swimming classification system, which was first used at the 1992 Barcelona Games, involves dry-land and water-based assessments to determine if athletes have an eligible impairment and allocate a sport class for competition. Athletes are allocated a sport class for specific swimming disciplines, including S (freestyle, backstroke, and butterfly), SB (breaststroke) and SM (individual medley) sport class prefixes. There are ten S and SM classes (e.g. S1-S10) and nine SB classes (SB1-SB9) for Para swimmers with an eligible physical impairment, three classes in each discipline for Para swimmers with vision impairment (e.g. S11-S13), and one class for each discipline for Para swimmers with intellectual impairment (e.g. S14). Para swimmers in the lower sport classes are estimated to have greater activity limitation in the swimming discipline than those in higher sport classes with the same type of impairment (i.e. physical or vision).

The variety in sport classes and classification processes within Para swimming has enabled the sport to have a proud history of inclusion for athletes with various impairments, but questions have been raised on the effectiveness of the classification system.[3,4] The International Paralympic Committee (IPC) has mandated that research be conducted to guide the development of evidence-based classification systems in Para sport, including swimming.[1] An evidence-based classification system aims to minimise the impact of impairment on the competition outcome by using methods that are proven efficacious by empirical research. The most critical research required to develop evidence-based classification systems involves developing valid measures that can be used to infer impairment, developing standardised sport-specific measures of performance, and assessing the relative strength of association between measures of impairment and sport-specific measures of performance.[5]

Studies in Para swimming have identified objective measures of impairment and established their relationship with swimming performance,[4,6-8] established the impact of eligible types of impairment on sport-specific measures of swimming performance to guide classification test protocols,[9-11] and established the impact of impairment on swimming performance to guide revisions in classification structures.[12,13] However, these cross-sectional studies do not provide an understanding on how measures of impairment, determinants of swimming performance, or the impairment-performance relationship vary at different stages of athletic development. Research is needed to understand how factors such as age and training mediate the impairment-performance relationship.[5] Such work is likely to be important to guide evidence-based classification in Para swimming given that athletes are most likely to receive classification prior to reaching their sporting potential.

There is a well-established link between age and competitive sport performance attributed to hormonal and physiological changes that occur in men and women across the life span.[14-17] The age of peak performance in swimming has increased over the last 40 years.[15,18] Early specialisation in swimming might have previously contributed to younger ages of peak performance and increases in funding and professionalism have enabled swimmers to achieve peak performance at older ages.[18] However, research over this period has consistently shown the age-related trajectory of swimming performance to be influenced by sex and event duration.[18,19] Women have been shown to reach peak performance at earlier ages than men, likely due to the earlier onset of puberty and associated changes of the musculoskeletal and cardiovascular systems and their contribution to swimming performance.[18,20] There have also been differences in the age of peak performance reported for sprint- (50 and 100 m) and long-distance swimmers (400 to 1500 m), with long-distance swimmers typically peaking at younger ages than sprint-distance swimmers.[18] This finding has been attributed to the training loads required of long-distance swimmers to achieve top performances and the potential impact of sustaining these training loads on injury risk and staleness.[14,18]

Currently, in contrast to non-disabled swimmers,[18,21] there is no information on the trajectory of performance in Para swimming over extended periods of time that reflect the transition of swimmers from development stages to elite level performance. Additionally, the influence of age, which impacts peak performance in other Para sports,[22] has not been investigated. It is possible that Para swimmers with impairment progress differently to non-disabled swimmers because of differences in training and performance characteristics, and the possibility that they commence training at older ages after acquiring impairment.[2,23] The variance in type and severity of eligible impairments in Para swimming also causes large differences in the training and performance characteristics between sport classes.[2,24,25] For example, Para athletes with high support needs experience challenges in accessing training facilities and appropriate coaching that might delay their progression in sport performance,[2,26] and the relative contribution of race segments to race distance is different for those with severe-to-moderate physical impairments (<S7) compared to Para swimmers in the higher sport classes.[25] These factors might influence the age-related trajectory of performance and explain differences in the age of peak performance between swimmers with and without impairment, and between Para swimmers with different type and severity of impairment.

Research that establishes the age-related trajectory of performance in Para swimmers can provide pertinent information for athlete benchmarking, development and classification. Accurate athlete benchmarking based on age, sex and classification would allow coaches and athletes to set realistic performance goals. Further, effective classification requires a thorough understanding of the factors that mediate the impairment-performance relationship in Para sport. Information on the age-related trajectory of performance, including the rate of progression and ages at which performance stabilises, would have implications for classification rules and regulations and the quality assurance of research that aims to establish the impairment-performance relationship in Para swimming. Therefore, this study aimed to establish the age-related trajectory of competitive performance in Para swimmers stratified by sex and sport class. It was hypothesised that: (i) Para swimmers reach peak performance in their early- to late-twenties, at similar or older ages than reported in non-disabled swimmers, (ii) women reach peak performance at younger ages than men, as reported in non-disabled swimmers, and (iii) type and severity of impairment effects the age-related trajectory of performance in Para swimmers.

Materials and methods

Study design

This study retrospectively analysed the annual best performances of Para swimmers with an eligible physical, vision or intellectual impairment listed on the World Para Swimming (WPS) classification master list. Mixed effects modelling was used to quantify the relationship between age and annual best performance and determine if sex and sport class interact with this relationship.

Participants

Data were obtained for 1825 Para swimmers that were on the WPS classification master list and had a minimum of one competitive performance in sanctioned long course swim meets from 2009 to 2019 (Supplementary Table 1). Data pertaining to sex, year of birth and sport class of Para swimmers were obtained from the 2019 summer season classification master list available on a public website (https://www.paralympic.org/swimming/classified-athletes). Para swimmers were only included in analysis if they were listed as having an eligible impairment. Broad classifications were allocated to Para swimmers based on their sport class, including severe-to-moderate physical impairment (S1-S6), moderate-to-minimum physical impairment (S7 to S10), vision impairment (S11 to S13) and intellectual impairment (S14). These broad classification groups were defined to enable the effect of type of impairment on the age-related trajectory of performance to be modelled with adequate rigour. The sport classes for Para swimmers with physical impairment were arbitrarily divided into two separate groups because of the higher number of athletes competing in these classes and the larger variance in activity limitation in these Para swimmers.[2] All data were obtained from publicly available websites and written confirmation from a Human Research Ethics Committee was received stating that ethics approval was not required for this study.

Performance data

Race times were obtained from the WPS athlete rankings list from 2009 to 2019 available on a public website (https://www.paralympic.org/swimming/rankings). Data were collected up to November 2019 and included results from the benchmark calendar competition, the 2019 London World Championships. Performances from short course (25 m pool) competitions were excluded from analysis. The analysis included performances for all strokes (freestyle, backstroke, butterfly, breaststroke and individual medley) over 50 m to 400 m distances if the athlete was eligible to compete in that discipline at the Paralympic games based on their sex and sport class. The individual medal events that are included in the Paralympic games for men and women are shown in Supplementary Table 2 and Supplementary Table 3, respectively. In total, 32041 annual performance times from 8663 cases and 1825 athletes were obtained (Supplementary Table 1). The number of recorded annual performances, personal best performance, and best athlete ranking was obtained for each case defined as the same athlete and swimming discipline. Annual performances were expressed as a percentage of the world record time for the respective Para swimming event (i.e. annual performance time (s) / world record time (s) x 100) and a percentage of Para swimmers' personal best times (annual performance time (s) / personal best performance time (s) x 100) to allow comparisons between sexes, sport classes and disciplines. For clarity of analysis, the term discipline designates a stroke and distance combination (e.g. 100 m backstroke) where an event would be regarded as a stroke and distance combination in a specific sex and sport class (e.g. Men's 100 m backstroke S5). The world record times for men's and women's swim events used in analysis can be found in Supplementary Table 2 and Supplementary Table 3, respectively.

Statistical analysis

Statistics were performed using R version 3.6.1.[27] Linear mixed effects modelling was used to model the age-related trajectory of annual best performances in the participant cohort. Linear mixed effects modelling is an extension of linear regression that allows analysis of hierarchical repeated measures data in which cases are not independent of one another (i.e. in this case repeated annual best performance times from different athletes in specific disciplines). Models were trained using the lme4 package[28] with annual best performance expressed as: (i) a percentage of personal best time, and (ii) a percentage of world record time included as response variables and age in years included as a fixed effect. Expressing the response variable in these ways enabled comparisons on the effect of age on performance in different swimming disciplines within and between sexes and sport classes. A factor variable that described the case (athlete and discipline) that times belonged was included as a random effect with case-specific slopes and intercepts. Sex and sport class were included as fixed effects in separate models to determine if these factors interact with the relationship between age and performance. The curvilinear relationship between age and annual best performance in this study was modelled using b-spline functions with the splines2 package (Figure 1).[29]

A systematic approach was used to train and appraise linear mixed effects models. First, a subset of the 32041 performance times (8663 cases and 1823 athletes) was obtained to improve model convergence and predictions from linear mixed effects modelling (Table 1). Cases in which athletes were above 35 years of age were excluded as they fell outside the 3rd quartile (75th percentile) plus 1.5 times the interquartile range and so were outlying cases. This resulted in a total of 2640 times (8.2%) from 613 cases (7.1%) and 147 athletes (8.1%) being excluded. Further, cases in which athletes did not have 7 or more annual performance times in the given discipline were excluded. These inclusion criteria were arbitrarily selected to increase the likelihood that performances of swimmers included in modelling had stabilised, and to avoid overfitting of spline regression for individual cases. This resulted in a further 18740 times (58.5%) from 6792 cases (77.7%) and 1265 athletes (69.4%) being excluded. The final subset that was used to train linear mixed effects models included 10661 times (33.3%) from 1258 cases (14.5%) and 411 athletes (22.5%). Case-specific residuals derived from predictions typically showed non-normal distributions characterised by large kurtosis and so outlying cases identified by absolute residuals above the 3rd quartile plus 1.5 times the interquartile range were removed from analyses. Models were appraised using the Akaike information criterion (AIC), likelihood ratio tests and by examining the goodness-of-fit.

Analyses showed that a considerable amount of the variance in annual best performance was explained by the random factor included in mixed effects modelling (i.e. athlete and discipline). Therefore, descriptive statistics (mean and standard deviations) of case-specific predictions were calculated to interpret the between-athlete variability in performance within age groups. Comparisons in case-specific predictions between adjacent age groups were examined using dependent t-tests with Bonferroni correction for multiple comparisons. Significance was set at an alpha value of $p \leq 0.01$ and estimated differences are reported with 90% confidence intervals.

Results

Linear mixed effects modelling showed there was a significant relationship between age and annual best performance expressed as a percentage of personal best time ($\chi^2 = 1244$, df = 5, $p < .001$) and a percentage of world record time ($\chi^2 = 1373$, df = 5, $p < .001$). Age explained a greater amount of variance in performance expressed as a percentage of personal best time (marginal $R^2 = .485$) than for performance expressed as a percentage of world record time (marginal $R^2 = .140$). The age-related trajectory of performance (percentage of personal best time) is characterised by gradually smaller annual improvements between the ages of 12 and 20 years (-0.7 – -11.3 %) before stabilising and peaking between the ages of 21 and 26 years and showing marginal annual regressions between the ages of 27 and 35 years (0.1 – 0.4 %) (Supplementary Figure 2G). A considerable amount of variance was explained by the random factor (athlete and discipline) included in linear mixed effects modelling evidenced by large inter-class correlations (ICC = .87 – .98) and conditional coefficients of determination (conditional $R^2 = .931 – .983$). These results show age is related to annual best performance although there is considerable variation in this relationship between athletes. The between athlete variation in the age-related trajectory of performance is characterised by large dispersion of case-specific predictions of performance expressed as a percentage of personal best performance between the ages of 12 and 20 years (Supplementary Figure 2H). The dispersion of performance between athletes is more consistent across ages for performance expressed as a percentage of world record time (Supplementary Figure 3H).

The inclusion of sex as an interaction term in linear mixed effects models resulted in marginal improvements in AIC and log-likelihood scores for performance expressed as a percentage of personal best time ($\chi^2 = 117$, df = 5, $p < .001$) and a percentage of world record time ($\chi^2 = 100$, df = 5, $p < .001$) (Table 2). The age-related trajectories of performance expressed as a percentage of personal best time and world record time for men and women are shown in Figure 2. The personal best performances of men tended to stabilise at 21 years of age, peak between 22 to 27 years of age, and show annual regressions of 0.1 – 0.2% from the age of 29 (Supplementary Table 4). Women were found to have faster times during adolescence (12 – 16 years) than men, and their personal best performances stabilise and peak earlier than men at 20 and 21 years of age. Women tended to have small annual regressions (0.1 – 0.7%) in personal best performance from 22-28 years of age, and from 28 years of age they showed larger annual regressions in personal best performance (0.3 – 0.7%) compared to men. These trends were similar when expressing performance as a percentage of world record time (Supplementary Table 5). Women tended to achieve times closer to the world record time than for men during early adolescence (i.e. 12 – 16 years), while men tended to achieve times closer to the world record time than for women at older ages (i.e. 22 – 35 years). However, performance expressed as a percentage of world record time tended to peak at older ages for men (29-30 years) and women (26-28 years) compared to projections of performances expressed as a percentage of personal best time (Figure 2).

Sport class was also found to interact with the relationship between age and annual best performance expressed as a percentage of personal best time ($\chi^2 = 172$, df = 18, $p < .001$) and world record time ($\chi^2 = 228$, df = 18, $p < .001$). The inclusion of sport class in linear mixed effects modelling had a noticeable impact on the amount of variance explained by fixed effects when performance was expressed relative to world record time (marginal $R^2 = .140$ versus .214) (Table 2). The mean age-related trajectory of performance was similar among sport classes between the ages of 12 and 20 years before performance stabilised (Figure 3), except swimmers in the S1-S6 classes generally had slower times relative to the world record than other sport classes (Figure 3b, Supplementary Table 7). This trend was consistent across all ages and linked to higher variation in performances between athletes within ages (Figure 3b, Supplementary Table 7).

Differences in the age-related trajectories between sport classes were more noticeable at ages after performance expressed as a percentage of world record time had stabilised (Figure 3b). Swimmers with mild physical impairment (S7-S10) and intellectual impairment (S14) were the most similar in their age-related performance trajectories, characterised by performance peaking between the ages of 25 and 27 years before showing small to moderate annual regressions (0.1 – 1.3%) between the ages of 28 and 35 years (Figure 3b, Supplementary Table 7). Swimmers with moderate to severe physical impairment (S1-S6) showed a similar age-related trajectory except these swimmers tended to have continued annual progressions in performance until the ages of 28 to 30 years before small annual regression were observed between 31 and 35 years (Figure 3, Supplementary Table 6, Supplementary Table 7). Swimmers with vision impairment (S11-S13) had a sustained annual improvement of 0 – 0.9% from the ages of 21 to 35 years and in contrast to all other sport classes, a decrement in performance was not observed in our analysis until performance peaked at 35 years of age (Figure 3b, Supplementary Table 7).

Discussion

This study provides the first information on the age-related performance trajectories relative to world record time and personal best time for Para swimmers with physical, vision and intellectual impairments. The main findings were: (i) Para swimmers show increasingly smaller annual progressions in performance between the ages of 12-20 years before performances stabilise and peak in the early- to late-twenties; (ii) women have faster times relative to personal best time and world record time during early adolescence than men and their performances stabilise and peak at younger ages; and (iii) there were differences in the age-related performance trajectories of swimmers from different sport classes, particularly during ages after maturation had occurred and when training-related factors are more likely to explain swimming performance.

The age of peak competitive performance in athletes ranges widely in different sports due to the attributes required for success and their varied progression and decline with maturation, aging and training.[14] Our results show the performances of Para swimmers generally stabilise and peak at the ages of 20-22 years when expressing performance relative to individual personal best time. These ages of peak performance are like those in Olympic swimmers with a top 10 ranking between 1980 and 2009,[15] but are younger than more recently reported for female (~23 years) and male swimmers (~24 years) ranked in the top 16 at the 2008 and 2012 Olympic games.[18] It is important to consider the differences in age-related trajectories of performance relative to personal best time and world record time in our study. The age-related trajectory of performance expressed relative to world record time showed Para swimmers achieve peak performances between 25 and 30 years of age (Supplementary Table 5). This suggests that the most successful Para swimmers (i.e. those that achieve a time close to the world record) can continue training and achieving marginal improvements in performance into their mid- to late-twenties.

The differences in the modelled age-related trajectories of performance relative to personal best time and world record time are marginal considering the magnitude of change in performance during this age span and large between-athlete variability in the trajectory of performance. It is possible the modelled estimates of performance relative to personal best time underestimate the typical ages at which performance stabilises and peaks in Para swimming. When performance was expressed as a percentage of personal best time there was a tendency for predictions derived from fixed effects models to overestimate the annual best performance for swimmers aged 16 and under (Supplementary Figure 2B). These younger swimmers that were included in analysis had not reached an age at which performance begins to stabilise, and therefore it is possible that their personal best times do not reflect their sporting potential. The predicted performances relative to world record time in our study were more consistent with the notion that swimmers can achieve progressions in performance after maturation and into their mid- to late-twenties. When expressing performance relative to world record time the population trend shows athletes achieve small annual improvements in performance (0.2–1.8%) after performance begins to stabilise at ages 18 and 20 years for women and men, respectively. Peak performance then occurs at 26-28 and 29-30 years for women and men, respectively, before gradual declines in performance (0.1–0.7%) occur until the age of 35 years. These ages of peak performance are older than those previously reported in non-disabled swimmers.[15,18] Nevertheless, studies have observed cardiorespiratory fitness and muscle function to peak and/or begin to decline during these ages (25-30 years) in untrained men and women[30-32] supporting the finding that Para swimmers can achieve annual progressions in competitive performance into their mid- to late-twenties with effective training similar to athletes in other sport events.[14]

The relationship between age and competitive performance in Para swimmers is most evident during early- to late-adolescence before performance begins to stabilise at approximately 20 years of age. This finding is consistent with research in non-disabled swimmers[18,33] and can be attributed to well-known physical and hormonal changes that occur during the stages of puberty.[20] There were differences in the age-related trajectory of performance between men and women that were most apparent during adolescence. These sex-differences were characterised by women having faster times relative to personal best time (3 – 20%) and world record time (6 – 21%) than men between the ages of 12-16 years, and the performances of women stabilising and peaking at younger ages than men. Peak height velocity during adolescence occurs earlier in females (11 years) than males (13 years), and so females might show earlier progressions in swimming performance due to increases in stature and limb length.[34-36] There are also notable sex-differences in changes in body composition, including lean muscle mass and fat mass, and cardiorespiratory endurance following maturation that determine swimming performance.[37] Some of these sex-differences may advantage women, for example, it is postulated that higher relative fat mass in the lower body is associated with lower underwater torque and improved exercise economy during swimming.[38,39] However, larger increases in lean muscle mass and cardiorespiratory endurance in males following puberty likely explain the greater overall progression in performance relative to personal best time for men (~48%) compared to women (~28%) from the age of 12 years. The finding of female Para swimmers' performances peaking earlier and declining at faster rate than men is consistent with previous research in track-and-field athletics, running and swimming.[17,18,40] This finding has previously been attributed to the ~2 year earlier onset of maturation in female swimmers,[18] although other training-related and socio-cultural factors could also explain these results.[17,41]

Our results show sport class, broadly describing the type and severity of impairment, influences the relationship between age and competitive swimming performance. The most notable differences were found for Para swimmers with vision impairment (S11-S13) that showed continued annual progressions in performance during the early-to-mid thirties unlike all other sport classes that showed annual declines in performance during this age span. The prolonged trajectory of performance progression in swimmers with vision impairment could be explained, at least in part, to differences in the rate of skill acquisition between those with intact vision and those with vision impairment. As vision impairment influences motor learning and skill acquisition it normally requires a longer time or more exposure to training to develop skills.[42,43] As identified recently by expert consensus,[4] severe vision impairment or blindness prevents the ability to exploit observational learning to model movements on those of others,[44] and prevents the enhancement of motor learning through observation via the mirror neuron system.[45] The trajectory of performance in athletes with vision impairment could be expected to continue for an extended period compared to swimmers with physical or intellectual impairment that commence training at similar ages.

Para swimmers with severe-to-moderate physical impairments (S1-S6) also showed notable differences in the age-related trajectory of performance compared with other sport classes. The projected estimates for these Para swimmers showed they were slower relative to the world record time across the entire age span compared to Para swimmers in other sport classes. This is consistent with previous research that has suggested Para athletes with moderate-to-severe physical impairment experience barriers to participation in training and competition that might affect performance progression and variability.[2,22,46] It is important that classifiers consider the larger between-athlete variability in competitive performance for these Para swimmers as differing contextual, environmental and personal factors could influence their age-related trajectory of performance. It is possible that these Para swimmers achieve high training volumes and intensities characteristic of high performance swimming over longer periods compared to their less impaired peers.[23,47] Indeed, Para swimmers with severe-to-moderate physical impairment (S1-S6) reached peak performance at older ages than Para swimmers with less severe physical impairment (S7-S10) by achieving larger annual progressions in performance after maturation (Figure 3B, Supplementary Table 7).

The results of this study have implications for classification rules and the quality assurance of research towards evidence-based classification methods in Para swimming. Age can be expected to have less of an impact on performance after 20 years of age, from which time factors such as training, genetics and severity of impairment are more likely to explain swimming performance. It is recommended that studies establishing the validity of measures of impairment and sport-specific measures of performance include eligibility criteria that ensures participants have reached an age at which point performance is likely to have stabilised. Similarly, these results might guide decisions on the allocation of sport class status that must be assigned with sport class in accordance with the International Standard for Athlete Evaluation. Sport class status will be one of 'confirmed', 'review' or 'review with a fixed review date' and indicates the extent to which an athlete may be required to undertake athlete evaluation and/or be subject to protest. It is recommended that a 'confirmed' sport class status is not assigned before the age of 20 years for Para swimmers with impairments that are permanent but not stable, or that involve the assessment of motor function when inferring loss of strength, motor coordination or range of motion resulting from impairment. Following the age of 20 years, the typical annual progressions in performance reported in this study can help determine the sport class status of athletes with fluctuating and/or progressive impairments or that have only recently entered competition after acquiring impairment. In such cases, classifiers should consider the type and severity of impairment when benchmarking performance progression, as the broad classification groups in this study were found to effect the age-related trajectory of performance after maturation and when training-related factors are more likely to explain swimming performance. It should be noted that Para swimmers in sport classes within the broad classification groups used in this study might show different age-related trajectories in performance due to large variance in type and/or severity of impairment.

Perspective

The performance trajectories that have been established in this study can guide talent identification and development strategies throughout a Para swimmer's sporting career. Coaches can benchmark performances based on age, sex and classification to set meaningful and realistic performance goals. There is considerable variation in the age-related trajectory of performance among Para swimmers and annual progressions in performance vary the most between the ages of 12-20 years. This highlights the possibility of low ranked junior Para swimmers outperforming their higher ranked peers once they reach their early to late twenties. Strategies that focus on maintaining participation rates in athlete development programs up until the age of 20 years might increase the number of medal potential athletes that make selection for major international meets at older ages. These results can also be used to guide decisions on the allocation of sport class status that must be assigned with sport class in accordance with the International Standard for Athlete Evaluation. It is recommended that Para swimmers with impairments that are permanent but not stable, or that involve the assessment of motor function, are not granted a confirmed sport class status until the age of 20 years or until their performances stabilise.

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Tables

Table 1. Participant characteristics for cases in subset included in linear mixed effects modelling with spline regression.

		Athletes n	Cases n	Times n	Age Median [$Q_1 – Q_3$]	Times per case Median [$Q_1 – Q_3$]	World Rankings Range	Time (% WR) Median [$Q_1 – Q_3$]
Men	All	239	707	6006	22 [19 – 25]	9 [7 – 10]	1 – 96	116 [110 – 125]
	S1-S6	59	163	1420	23 [17 – 27]	9 [8 – 10]	1 – 80	125 [113 – 141]
	S7-S10	109	340	2889	21 [17 – 24]	9 [7 – 10]	1 – 109	115 [109 – 122]
	S11-S13	46	149	1239	24 [17 – 27]	8 [7 – 10]	1 – 56	114 [109 – 122]
	S14	25	55	458	22 [17 – 24]	9 [8 – 10]	1 – 96	114 [109 – 120]
Women	All	172	552	4655	20 [17 – 23]	9 [7 – 10]	1 – 98	119 [111 – 129]
	S1-S6	40	130	1094	21 [17 – 24]	8 [7 – 10]	1 – 53	124 [113 – 137]
	S7-S10	85	295	2469	19 [17 – 22]	8 [7 – 10]	1 – 98	117 [110 – 126]
	S11-S13	32	87	754	21 [17 – 24]	9 [8 – 10]	1 – 34	116 [110 – 123]
	S14	16	40	338	22 [17 – 25]	9 [8 – 10]	1 – 57	122 [114 – 130]
Total		411	1258	10661	21 [18 – 24]	9 [7 – 10]	1 – 98	117 [110 – 127]

Table 2. Model appraisal information for linear mixed effects models with b-spline functions with and without categorical interaction terms included.

	Model 1 (Age)	Model 2 (Age*Sex)	Model 3 (Age*Class)
Percent of personal best time			
Observations	10110	10110	10110
Cases	1258	1258	1258
Athletes	411	411	411
AIC	49113	49009	48954
log-Likelihood	-24529	-24470	-24431
Marginal R^2	.486	.498	.485
Conditional R^2	.931	.926	.925
ICC	.866	.852	.855
RMSE	1.56	1.56	1.57
Percent of world record time			
Observations	10027	10027	10027
Cases	1258	1258	1258
Athletes	411	411	411
AIC	57441	57337	57190
log-Likelihood	-28693	-28635	-28549
Marginal R^2	.140	.140	.214
Conditional R^2	.983	.983	.983
ICC	.981	.980	.978
RMSE	1.81	1.81	1.80

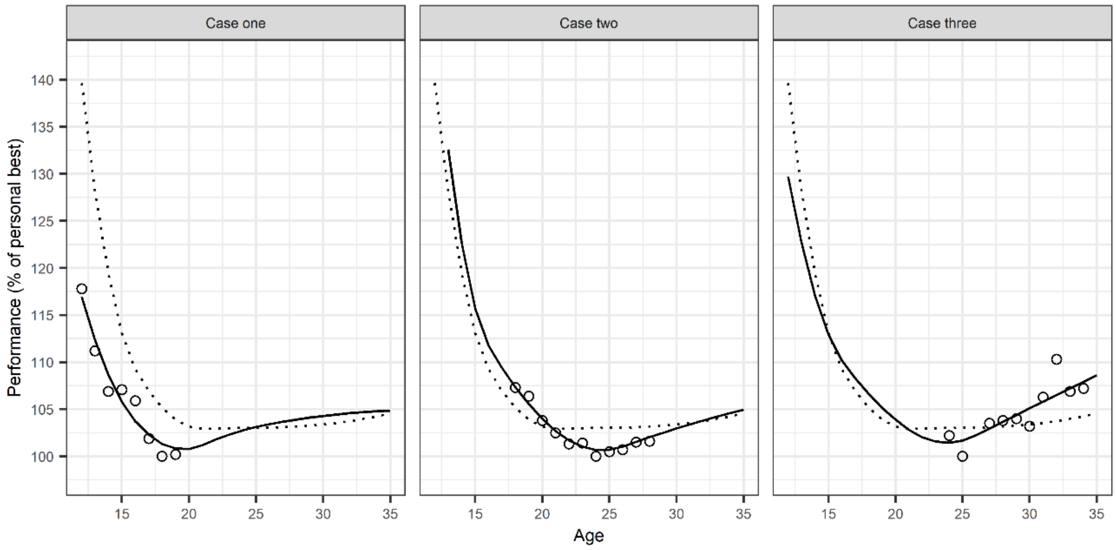
Model 1, Model 2, and Model 3 are linear mixed effects models with b-spline functions without interaction terms, with sex included as an interaction term, and with classification included as an interaction term, respectively. AIC: Akaike Information Criterion. R^2: coefficient of determination. ICC: Inter-class correlation coefficient. RMSE: root mean square error.

Figures legends

Figure 1. Example of predicted performance trajectories for three Para swimmers in their best ranked event using linear mixed effects modelling with spline regression. The symbols indicate annual best performances expressed as a percentage of personal best time and the black lines indicate predicted performance trajectories for individual Para swimmers. The dotted grey line shows the mean population fit (i.e. average prediction) for the entire cohort of Para swimmers included in modelling. Each of these Para swimmers have achieved a number 1 World Rank in their career.

Figure 2. Boxplots showing the median and dispersion of projected annual best performance expressed as a percentage of (A) personal best time and (B) world record time for Para swimmers stratified by sex. The light grey lines show case-specific predictions of annual best performance for individual athletes that were derived from linear mixed effects modelling with b-spline functions. The descriptive statistics shown by the boxplots attempt to characterise the age-related trajectory and between-athlete variability in annual best performance.

Figure 3. Boxplots showing the median and dispersion of projected annual best performance expressed as a percentage of (A) personal best time and (B) world record time for Para swimmers stratified by classification. The light grey lines show case-specific predictions of annual best performance for individual athletes that were derived from linear mixed effects modelling with b-spline functions. The descriptive statistics shown by the boxplots attempt to characterise the age-related trajectory and between-athlete variability in annual best performance.



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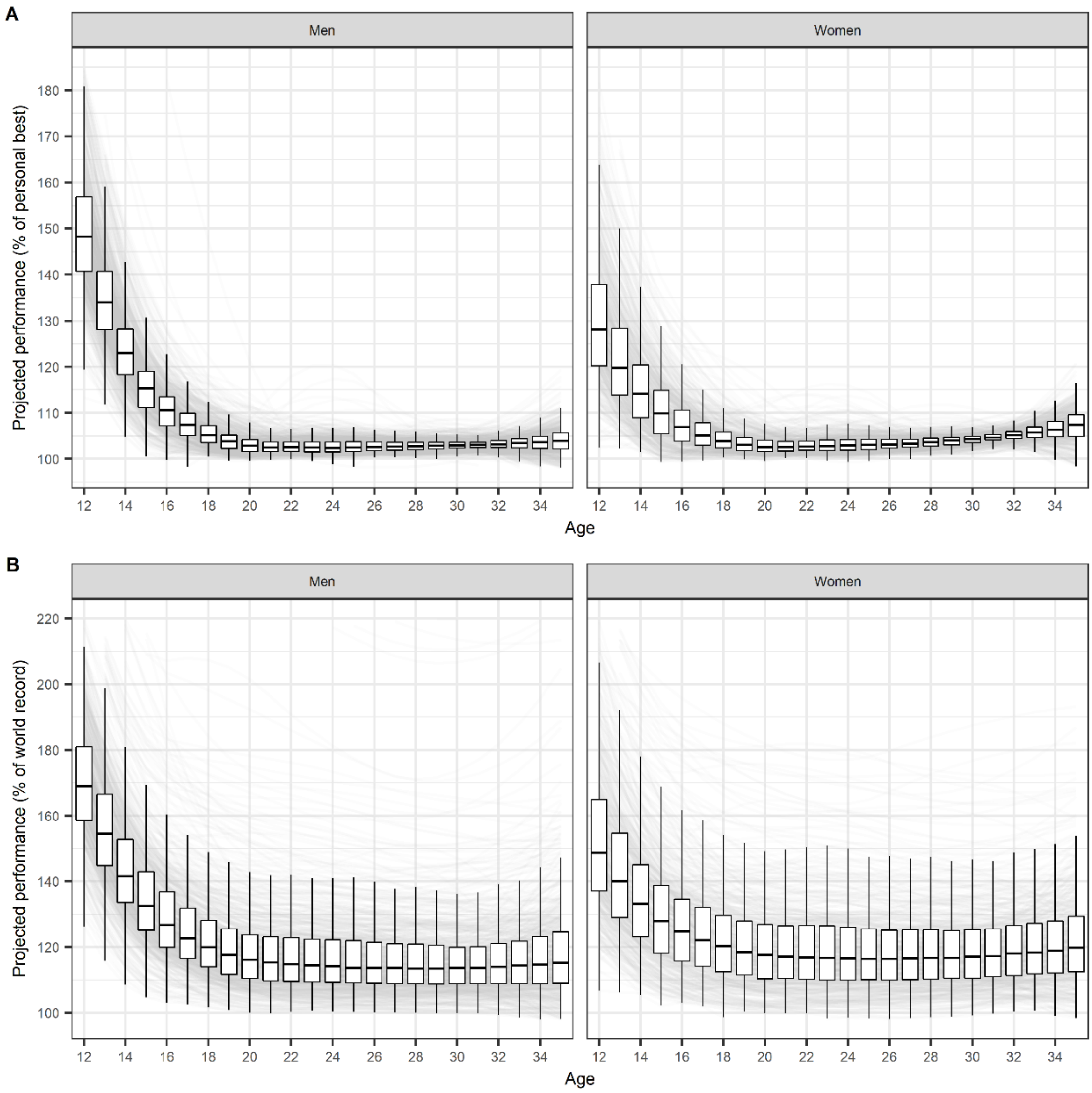

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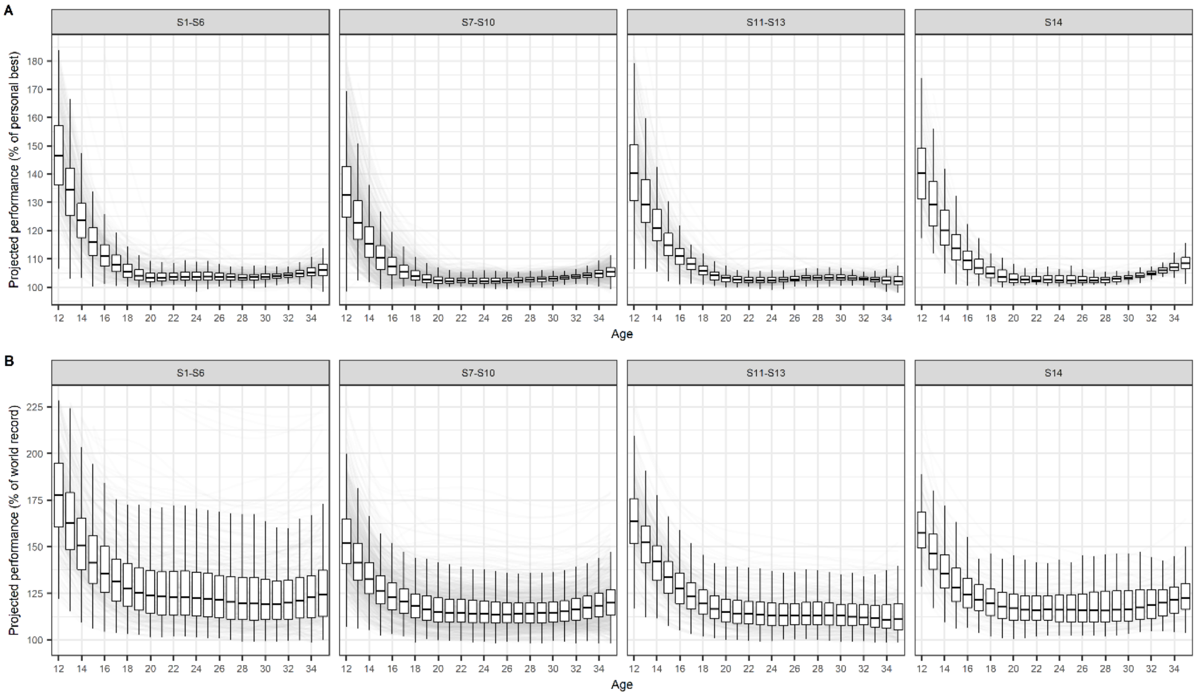

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