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AUTOREFERAT ROZPRAWY DOKTORSKIEJ

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Czynniki morfologiczne, fizjologiczne oraz właściwości kinematyczne determinujące wyniki sportowe młodych pływaków w kraulu na piersiach

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Serdeczne podziękowania za życzliwość,
poświęcony czas oraz nieocenioną pomoc na
każdym etapie tworzenia pracy kieruję do mojego
Promotora Pana ***dr hab. Marka Strzały***.
Dziękuję wszystkim Kolegom i *Koleżankom*, którzy
służyli fachową pomocą w *realizacji badań*
i przyczynili się do powstania niniejszej dysertacji.
Pracę dedykuję moim Rodzicom i Bliskim, *będąc*
wdzięcznym za okazane wsparcie
i wiarę w moje możliwości.

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1. Wykaz skrótów i symboli

BA (lata) – z ang. biological age, wiek biologiczny. Podawany w latach tak jak wiek kalendarzowy, określany przez antropologa na podstawie np. trzeciorzędowych cech płciowych, siatek centylowych. Wskazuje stopień zaawansowania procesu dojrzewania.

LTAD – z ang. long term athlete development – długookresowy rozwój sportowca. Koncepcja długookresowego szkolenia sportowców od lat najmłodszych do wieku seniorskiego (Balyi i Way, 2004).

SL (m) – z ang. stroke length, długość cyklu ruchowego. Odległość jaką pokonuje ciało pływaka w trackie jednego pełnego cyklu ruchowego pracy ramion.

SR (cykl · min^{-1}) – z ang. stroke rate, liczba cykli ruchowych ramion wykonywanych w czasie jednej minuty.

SI ($m^2 \cdot s^{-1}$) – z ang. stroke index, jest wskaźnikiem efektywności techniki pływania. Jest iloczynem *SL* i prędkości pływania.

AT – próg anaerobowy AT (z ang. anaerobic threshold) (Beaver i wsp. 1986).

RCP – próg wentylacyjny RCP (z ang. respiratory compensation point) (Beaver i wsp. 1986).

$\dot{V}O_2max$ ($l \cdot min^{-1}$ lub $ml \cdot kg \cdot min^{-1}$) – maksymalny minutowy pobór tlenu.

VO_2peak ($l \cdot min^{-1}$ lub $ml \cdot kg \cdot min^{-1}$) – szczytowy pobór tlenu.

$V_{AT}, V_{RCP}, V_{\dot{V}O_2max}$ ($m \cdot s^{-1}$) – prędkość pływania osiągana w momencie wystąpienia fizjologicznych progów: *AT*, *RCP* oraz podczas uzyskania $\dot{V}O_2max$.

V_{STF} ($m \cdot s^{-1}$) – średnia prędkość pływania w strefach skoku startowego, nawrotu i finiszu.

$V_{surface}$ ($m \cdot s^{-1}$) – średnia prędkość pływania w strefie pływania powierzchniowego.

V_{total} ($m \cdot s^{-1}$) – średnia prędkość pływania na całym dystansie.

CMJ (N) – z ang. counter movement jump, wyskok pionowy.

F_{max} (N) – maksymalna wartość siły osiągnięta w teście.

F_{ave} (N) – średnia wartość siły z testu.

$F_{decline}$ (N) – spadek wartości siły w teście.

I_{ave} (N) – średni popęd siły na cykl pracy ramion.

ICC – z ang. Intra-class correlation coefficient. Współczynnik korelacji międzyklasowej.

2. Spis publikacji wchodzących w skład cyklu dysertacyjnego

Przedstawiona rozprawa doktorska została przygotowana w formie cyklu 4 publikacji naukowych powiązanych ze sobą tematycznie (załącznik nr 3). Jestem pierwszym autorem tych prac, przyjmując na siebie główną rolę w projektowaniu, przeprowadzeniu niezbędnych badań, a także w późniejsze przygotowanie wspomnianych publikacji dysertacyjnych. Załącznik nr 1 stanowi zawiera potwierdzenie procentowego udziału pracy w powstanie publikacji.

Publikacja nr 1

Sokołowski, K., Strzała, M., Stanula, A., Kryst, Ł., Radecki-Pawlik, A., Krężałek, P., Rosemann T., Knechtle, B. (2021). Biological age in relation to somatic, physiological, and swimming kinematic indices as predictors of 100 m front crawl performance in young female swimmers. *International Journal of Environmental Research and Public Health*. 18(11): 6062. DOI: 10.3390/ijerph18116062
– 140 pkt MNiSW, 3.364 IF

Publikacja nr 2

Sokołowski, K., Strzała, M., Żegleń, M. (2022). Study of talented young male swimmers–scientific approach to the kinematic and physiological predictors of 400-m front crawl race. *Acta of Bioengineering and Biomechanics*. 24(1). DOI: 10.37190/ABB-01964-2021-02
– 100 pkt MNiSW, 1.238 IF

Publikacja nr 3

Sokołowski, K., Strzała, M., Radecki-Pawlik, A. (2022). Body composition and anthropometrics of young male swimmers in relation to the tethered swimming and kinematics of 100-m front crawl race. *International Journal of Sports Medicine and Physical Fitness*. DOI: 10.23736/S0022-4707.22.14054-5
– 40 pkt MNiSW, 1.669 IF

Publikacja nr 4

Sokołowski, K., Bartolomeu, R., Barbosa, T.M, Strzała, M. (2022). $\dot{V}O_2$ kinetics and tethered strength influence the 200-m front crawl stroke kinematics and speed in young male swimmers. *Frontiers in Physiology*. 13: 2443. DOI: 10.3389/fphys.2022.1045178
– 100 pkt MNiSW, 4.755 IF

Powyższe publikacje wchodzące w skład cyklu uzyskały sumarycznie 380 punktów MEiN oraz 11.026 punktów Impact Factor.

Pozostałe publikacje autorstwa doktoranta nie wchodzące w skład cyklu:

1) Strzała, M., Stanula, A., Krężałek, P., Sokołowski, K., Wądrzyk, Ł., Maciejczyk, M., Karpiński, J., Rejdych, W., Wilk, R., Sadowski, W. (2022). Correlations between Crawl Kinematics and Speed with Morphologic, Functional, and Anaerobic Parameters in Competitive Swimmers. *International Journal of Environmental Research and Public Health*. 19(8):4595. DOI:10.3390/ijerph19084595.
2) Strzała, M., Stanula, A., Krężałek, P., Sadowski, W., Wilk, R., Pałka, T., Sokołowski, K., Radecki-Pawlik, A. (2020). Body composition and specific and general strength indices as predictors of 100-m front crawl performance. *Acta of Bioengineering and Biomechanics*. 22(4):51-60. DOI: 10.37190/ABB-01665-2020-02.
3) Sokołowski, K., Strzała, M., Stanula, A. (2020). Different forms of swimmers' final weeks pre-competition preparation. *Baltic Journal of Health and Physical Activity*. 12(4): 10. DOI: 10.29359/BJHPA.12.4.10.

Powyższe publikacje nie wchodzące w skład cyklu uzyskały sumarycznie 310 punktów MEiN oraz 5.687 punktów Impact Factor.

Część I

Autoreferat

3. Wstęp

3.1. Badania nad sprawnością pływacką młodych zawodników, identyfikacja talentów – dotychczasowy stan wiedzy, kierunek rozwoju

Trenerzy na całym świecie stoją przed trudnym zadaniem poszukiwania i rozpoznania uzdolnień sportowych u młodych zawodników, które wspierane odpowiednim treningiem umożliwią im osiąganie wysokich wyników w dalszych etapach kariery. Znane są różne definicje talentu sportowego, Brown (2001) określa go jako „wyraźnie wyższe od przeciętnych umiejętności sportowe w porównaniu z innymi uczestnikami w tym samym wieku, jak również potencjał do osiągania sukcesów w zawodach na najwyższym poziomie." Obecnie proponowane są różne modele (zwane „ścieżkami") rozwoju zawodnika w pływaniu. Wszystkie z nich ukierunkowane są na racjonalne postępowanie wspierające systematyczny progres wyniku sportowego (Allen i wsp., 2014). Inne koncepcje sięgają do rozwoju kariery na poziomie elity w dorosłości (Coté, 1999; Lloyd, 2012). Jedną z najbardziej znanych koncepcji prowadzenia zawodników do mistrzostwa sportowego w wielu dyscyplinach włączając w to pływanie jest model *LTAD* (z ang. Long Term Athlete Development) (Balyi i Hamilton, 2004). Realizacja tej koncepcji szkolenia jest przystępnie przybliżona badaczom i praktykom (Balyi i Way, 2005; Ford i wsp., 2011) i została z powodzeniem zaadaptowana przez niektóre pływackie związki narodowe, głównie z krajów anglosaskich takich jak np. Wielka Brytania, Kanada. Podstawowym założeniem koncepcji *LTAD* jest masowe szkolenie dzieci i młodzieży na początkowych etapach treningu z dbałością o zdrowie i harmonijny rozwój fizyczny. Modele postępowania treningowego proponowane w ramach *LTAD* sugerują stosowanie treningu sportowego składającego się z wielu czynności (aktywności ruchowych) od najmłodszych lat, aby rozwinąć różnorodne wzorce ruchowe, a także uwzględniać interakcję dojrzewania z reakcją organizmu na bodźce treningowe. Taki model ma być przyjazny dla dużej liczby potencjalnych talentów sportowych umożliwiając metodyczne, łagodne prowadzenie szkolenia sportowego na drodze do sportu elitarnego w życiu dorosłym (Lang i Light, 2010).

Programy szkolenia sportowego w pływaniu są efektem próby połączenia wniosków z badań naukowych z praktyką treningową. Dotyczy to nie tylko doboru właściwych obciążeń treningowych oraz doskonalenia techniki pływania, lecz także identyfikacji istotnych zmiennych wskazujących na posiadanie talentu przez młodego sportowca (Balyi i Way, 2005). Naukowcy starają się wskazać zależności pomiędzy tymi zmiennymi, by znając ich poziom, wspierać osoby obdarzone odpowiednimi cechami, a następnie zwiększyć ich szansę w rywalizacji z tymi mniej utalentowanymi (Morais i wsp., 2012). W badaniach obejmujących młodych zawodników coraz częściej sięga się do szerokiego zestawu zmiennych z obszaru fizjologii wysiłku pływackiego (Lätt i wsp., 2010; Strzała i Tyka, 2009), biomechaniki (Barbosa i wsp., 2010; Jürimäe i wsp., 2007; Figueiredo i wsp., 2016), antropometrii (Geladas i wsp., 2005; Lätt i wsp., 2009) aby spośród tych obszarów wyłonić zmienne najmocniej powiązane z wysokim wynikiem sportowym (Latt i wsp., 2010; Jurimae i wsp., 2007).

Stopień dojrzałości biologicznej indukuje niemal każdy aspekt sprawności młodego sportowca. Jej poziom wpływa na zdolność do wytwarzania energii w procesie aerobowym, anaerobowym, właściwości siłowe, a także inne, jak umysłowe (Baxter-Jones i wsp., 1995; Malina i wsp., 1997; Russell i Startup, 1986). Abbott i wsp. (2021) wskazują, że stopień dojrzałości biologicznej (*BA*) jest istotnie powiązany z zaawansowaniem technicznym, a przez to z prędkością pływania młodych sportowców. Nieumiejętność dostrzeżenia wpływu *BA* na wyniki sportowe może prowadzić do stawiania błędnych wymagań co do bieżącego ich ukształtowania u młodych zawodników, a poprzez taki krótkookresowy pogląd, również błędnej oceny wartości tych młodocianych do osiągania wysokich wyników w dorosłości (Armstrong i wsp. 2015).

Zmienne antropometryczne zostały wielokrotnie zidentyfikowane jako te, które istotnie determinują wyniki młodych pływaków. Mezzaroba i Machado (2013) wskazali na bezpośrednią zależność zaawansowania *BA* i wynikających z tego różnic w wymiarach długościowych ciała na ukształtowanie podstawowych wskaźników kinematycznych charakteryzujących technikę pływacką – *SR, SL, SI* (*stroke length, stroke index*, Craig i Pendergast, 1979). Silną zależność wysokości ciała lub jej całkowitej długości i sprawności pływackiej w okresie dojrzewania potwierdzają także inne badania (de Mello Vitor i Böhme, 2010; Oliveira i wsp., 2021). Wskazano, także na odbywający się w sporcie pływackim dobór osobniczy, bowiem w wieku dziecięcym i młodzieńczym pływacy są średnio wyżsi niż ich rówieśnicy nie uprawiający sportu lub uprawiający inne dyscypliny: piłkę nożną, gimnastykę, tenis (Baxter-Jones i wsp., 1995; Damsgaard i wsp., 2000). Znane są również doniesienia na temat związku składu ciała pływaków z ich zdolnościami do generowania napędu i co za tym idzie z wynikiem pływackim (Cortesi i wsp., 2020; Pyne i wsp., 2006; Strzała i wsp., 2020). Niemniej w sporcie dorosłych, elitarnych pływaków zaobserwowano, iż osiągane są odpowiednie wymiary długościowe ciała (Gagnon i wsp., 2018, Toussaint i wsp., 1990), jednak sama długość ciała nie gwarantuje całkowitej przewagi (Kjendlie i Stallman, 2011). Dlatego, by przechylić szalę ku sukcesowi pozostaje zwiększanie efektywności techniki pływackiej (Morais i wsp., 2012).

Wysoka sprawność sytemu aerobowego wytwarzania energii mięśniowej wiąże się z większymi możliwościami osiągania wysokich wyników nie tylko na dystansach średnich i długich (200-m i więcej) lecz także na krótkich (Olbrecht, 2000). Udowodniono, że poziom $\dot{V}O_2max$ u młodych pływaków jest obok zmiennych biomechanicznych (funkcjonalnych) (np. *SL*, *SI*) najmocniej powiązanym z wysokimi rezultatami w wyścigu (sprawdzianie) na 400-m kraulem na piersiach (Jürimäe i wsp., 2007; Lätt i wsp. 2009). Sprawność krążeniowo-oddechowa, konsumpcja tlenu i wytwarzanie energii u młodych sportowców bardziej zaawansowanych w procesie dojrzewania jest wyższa niż u ich mniej rozwiniętych rówieśników, a różnice te według Maliny i wsp. (1997) sięgają 0,2 - 1,0 $l \cdot min^{-1}$. Kavouras i Troup (1996) na podstawie pomiarów w kanale przepływowym stwierdzili, że wydolność aerobowa dorastających pływaków wyrażona maksymalnym minutowym poborem tlenu osiąga szczytowe tempo przyrostu w wieku 14-15 lat u dziewcząt oraz 15-16 lat u chłopców. Ponadto, Baxter-Jones i wsp. (1993) w swoich badaniach długookresowych dostrzegli, że młodzież późno-dojrzewająca osiąga ostatecznie wyższy poziom $\dot{V}O_2max$. Wskazali oni również, że w przeciwieństwie do dziewcząt, u chłopców w końcowym okresie dojrzewania nadal występuje istotny przyrost $\dot{V}O_2max$.

Zmienne kinematyczne ruchu pływackiego jak długość cyklu ruchowego - *SL* (*stroke length*), w którym przemieszcza się ciało pływaka oraz iloczyn *SL* i prędkości pływania (*SI*) zostały przez wielu badaczy uznane za najlepiej wyjaśniające (np. w statystycznych modelach regresyjnych) sprawność pływacką młodych zawodników (Jürimäe i wsp., 2007; Lätt i wsp., 2009; Saavedra i wsp., 2010). Jurimae i wsp. (2007) wskazują, iż *SI* jest wskaźnikiem najlepiej określającym efektywność wytrenowanej techniki pływackiej przed i w trakcie okresu dojrzewania. Mezzaroba i Machado (2013), również wskazali na *SI* jako na najlepszy wskaźnik opisujący zaawansowanie techniczne młodych zawodników analizując ich wyścigi na 100 i 400-m kraulem na piersiach. Barbosa i wsp. (2019) określili wysoki *SL* jako jeden ze wskaźników wyróżniających najlepszych pływaków w przedziale wiekowym 11-13 lat.

Dowiedziono, iż u młodych pływaków anaerobowa komponenta wydolności jest mniej rozwinięta niż u zawodników dorosłych, co wskazuje na istotny wpływ dojrzewania biologicznego na jej poziom (Bencke i wsp., 2002). Vorontsov i wsp. (1999) wskazali, że stopień dojrzałości biologicznej najmocniej determinuje poziom zdolności siłowo-szybkościowych w wieku 13-14 lat u dziewcząt oraz 14-15 lat u chłopców. Odpowiedni poziom zdolności siłowych umożliwiający intensywniejszą pracę, zapewnia zwiększoną zdolność do generowania siły napędowej i jest kluczowym zasobem niezbędnym w rywalizacji na dystansach sprinterskich i średnich, już w wieku nastoletnim (Kalva-Filho i wsp., 2017). Jednym z testów służącym ocenie zdolności do wytwarzania siły napędowej w sposób specjalistyczny dla sportu pływackiego wykorzystywane jest pływanie na uwięzi z pomiarem siły ciągu (Amaro i wsp., 2014). Wyniki tej próby istotnie korelują ze sprawnością pływacką na dystansach krótkich (Geladas i wsp., 2005; Taylor i wsp., 2003). Zróżnicowanie wartości wskaźników (siła średnia, siła maksymalna, – średni popęd siły wytwarzany w cyklu ruchowym), uzyskiwanych podczas testu pływania na uwięzi (Taylor i wsp., 2003) można powiązać z rozwojem wysiłkowej energetyki anaerobowej organizmu. Tego rodzaju dane mogą dostarczyć badania pływaków wykonywane w warunkach najbardziej adekwatnych, specyficznych -wodnych (Dopsaj i wsp., 2003).

Najważniejsze dociekania badawcze w zakresie sportu pływackiego dzieci i młodzieży wskazują na kilka obszarów, które mają największy wpływ na wynik sportowy w pływaniu. Na przykład Figueiredo i wsp. (2016) wskazują w odpowiedniej kolejności, najpierw na budowę somatyczną, determinującą opanowanie efektywnej techniki pływackiej, która jest ukształtowana odpowiednim postępowaniu treningowym. Inni (m.in.. Barbosa i wsp. 2010) wskazują, że to profil energetyczny determinuje wyższe zaawansowanie techniczne i w związku z tym w największym stopniu wpływa na sukcesy młodych pływaków. Z kolei Lätt i wsp. (2010) wskazują, że właściwości somatyczne, energetyczne oraz kinematyczne detale techniki pływackiej tworzą indywidualny dla każdego pływaka model wyjaśniający wynik sportowy.

Obecnie w ramach odbywających się na pływalniach wyścigów pływackich w stylu dowolnym rozgrywana jest największa liczba konkurencji: 50-m, 100-m, 200-m, 400-m, 800-m oraz 1500-m. Niemal wszyscy zawodnicy w ramach stylu dowolnego stosują najszybszą technikę pływania - kraulem na piersiach. Z zastosowaniem tej techniki młodzi zawodnicy, również pokonują proporcjonalnie największy metraż treningowy, bez względu na kształtującą się w tym wieku specjalizację stylową. W tych okolicznościach kraul na piersiach w porównaniu do innych technik jest dominujący i najczęściej podlega rozważaniom badawczym w sporcie pływackim (Troup, 1991; Barbosa i wsp. 2013).

W podjętych przez autora rozprawy rozważaniach naukowych z zakresu badań nad czynnikami wyjaśniającymi wysoką sprawność pływacką, dostrzeżono lukę, tym samym możliwość realizacji badań własnych w celu uzupełnienia stanu wiedzy w zakresie wpływu czynników morfologicznych, fizjologicznych oraz właściwości kinematycznych ruchu pływackiego, determinujących wyniki sportowe młodych sportowców pływaniu kraulem na piersiach.

3.2. Cel badań oraz hipotezy

Celem rozprawy było określenie wpływu zmiennych morfologicznych, fizjologicznych oraz właściwości kinematycznych pływania kraulem na piersiach na sprawność pływacką młodych zawodników w przedziale wiekowym 12-15 lat. W przeprowadzonych badaniach zastosowano nowatorsko zaplanowane i zaprojektowane na potrzeby badań urządzenia i stanowiska pomiarowe. Wykonano pomiary wydolności anaerobowej i aerobowej, w sposób specyficzny dla sportu pływackiego. Uwzględniono także pomiary z zakresu antropometrii, składu tkankowego ciała i określenia wieku biologicznego pływaków. Efektem tych pomiarów było wyłonienie zestawu czynników istotnie determinujących sprawność pływacką młodych zawodników w wyścigach kraulem na piersiach na krótkich i średnich dystansach (w ramach pływania stylem dowolnym). W obranym postępowaniu badawczym zdecydowano się na ocenę wieku biologicznego badanych pływaków, a następnie wykorzystanie odpowiednich technik obliczeń statystycznych, gdzie zastosowano korelacje cząstkowe z kontrolą czynnika wieku biologicznego lub analizę mediacji pomiędzy zmiennymi z estymacją wpływu wieku biologicznego. Umożliwiło to wyodrębnienie wpływu *BA* na zależność poszczególnych zmiennych ze sprawnością pływacką. Sformułowano następujące hipotezy:

1) Poziom wybranych wskaźników – predyktorów morfologicznych, fizjologicznych może w zróżnicowany sposób determinować sprawność pływacką w grupie badanych młodych zawodników,
2) Poziom progów *AT*, *RCP* oraz maksymalnego poboru tlenu, mierzonych w teście stopniowanym w kanale przepływowym oraz poziom szczytowego poboru tlenu zmierzonego w teście minutowym są czynnikami istotnie determinującymi

rezultaty pływackie zarówno w średnich, jak i krótkich wyścigach w kraulu na piersiach,

3) Wybrane wskaźniki związane z siłą generowaną w pływaniu na uwięzi znacząco determinują bieżącą dyspozycję w pływaniu wyścigów kraulem na piersiach na różnych dystansach wśród młodych pływaków,
4) Wybrane właściwości morfologiczne (rozmiary i skład ciała) oraz fizjologiczne (poziom maksymalnego minutowego poboru tlenu, szczytowego poboru tlenu) determinują właściwości kinematyczne techniki kraula na piersiach,
5) Wiek biologiczny ma wpływ na zależność pomiędzy wyznaczonymi zmiennymi (antropometrycznymi, fizjologicznymi, kinematycznymi) a wynikiem sportowym na średnim i krótkim dystansie w pływaniu kraulem na piersiach.

Weryfikacji wyżej wymienionych hipotez dokonano w czterech artykułach naukowych, które opublikowano na łamach czasopism naukowych. Założenia i cele badawcze każdego artykułu zebrano poniżej:

Publikacja nr 1. Celem badań było wyłonienie zmiennych najlepiej wyjaśniających sprawność pływacką młodych zawodniczek w wyścigu na dystansie 100-m kraulem na piersiach. W badaniach tych zmierzono i wyszczególniono pulę zmiennych fizjologicznych, morfologicznych oraz biomechanicznych, a ich wpływ na rezultaty sportowe oceniono z kontrolą odziaływania wieku biologicznego. W ramach pomiarów wykonano test stopniowany w kanale przepływowym z użyciem nowoopracowanej aparatury.

Publikacja nr 2. Za cel badań postawiono identyfikację kluczowych zmiennych fizjologicznych oraz kinematycznych powiązanych z wynikiem sportowym młodych pływaków płci męskiej w wyścigu na dystansie 400-m kraulem na piersiach. Szczegółowej analizie poddano wskaźniki kinematyczne techniki i ich zmiany na przestrzeni całego wyścigu.

Publikacja nr 3. W tej publikacji poszukiwano zależności pomiędzy budową somatyczną (w szczególności skład ciała oraz wymiary antropometryczne) a rezultatami wyścigu na 100-m kraulem na piersiach chłopców. Określono również ich wpływ na wskaźniki kinematyczne opisujące technikę pływania. Rozpatrywano zależności wskaźników wytwarzanej siłowy ciągu pływania na uwięzi z szacowaną masą mięśniową poszczególnych partii ciała.

Publikacja nr 4. Poszukiwano determinantów fizjologicznych, biomechanicznych oraz morfologicznych powiązanych z wysoką sprawnością pływacką młodych zawodników płci męskiej na dystansie 200-m kraulem na piersiach. Wykonano jednominutowy test z pomiarem szczytowego poboru tlenu podczas 60 sekundowego pływania na uwięzi. Przedstawiono także uśrednione dane pomiarowe dla przedziałów wieku biologicznego sportowców.

4.1. Organizacja badań, grupa badanych

Badania zostały przeprowadzone w obiekcie krytych pływalni Akademii Wychowania Fizycznego w Krakowie w dwóch seriach badań. Na ich przeprowadzenie uzyskano zgodę Komisji Bioetycznej przy Okręgowej Izbie Lekarskiej w Krakowie (załącznik nr 2). W badaniach wzięli udział pływacy kadry wojewódzkiej Małopolskiego Okręgowego Związku Pływackiego w przedziale wiekowym 12-15 lat. W pierwszej serii badań brało udział 38 pływaków obojga płci (19 dziewcząt oraz 19 chłopców), natomiast w drugiej 95 (44 dziewczęta oraz 51 chłopców). W każdej serii badań uczestnicy dostarczyli pisemną zgodę swoich opiekunów prawnych na udział w badaniach.

4.2. Pomiary morfologiczne

Pomiary budowy ciała dokonane zostały przez doświadczonych antropologów, pracowników Zakładu Antropologii AWF Kraków. Wykorzystywali oni urządzenia pomiarowe Sieber Hegner Maschinen AG (Szwajcaria), wraz z nierozciągliwą taśmą antropometryczną i fałdomierzem zegarowym. Do określenia składu ciała użyto wagi elektronicznej Tanita BC-418 (Japonia). Określono również wiek biologiczny badanych.

4.3. Pomiary funkcjonalne, wydolność aerobowa

Głównym założeniem pomiarów fizjologicznych było określenie poziomu wydolności anaerobowej i aerobowej organizmu zawodników. Wydolność aerobowa była mierzona była w ramach testów w środowisku wodnym, gdzie wykonywano:

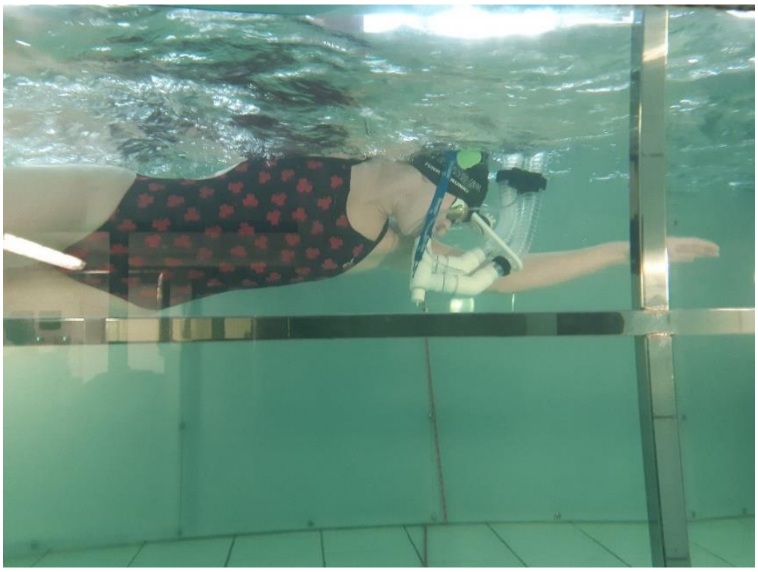
a) stopniowany test wysiłkowy w trakcie pływania kraulem na piersiach w kanale przepływowym z pomiarem parametrów oddechowych. Wyznaczono progi przemian związane z energetyką metabolizmu wysiłkowego, wyznaczano: 1) próg anaerobowy (AT) oraz 2) próg kompensacji oddechowej (RCP) (Beaver i wsp., 1986), a także maksymalny minutowy pobór tlenu ($\dot{V}O_2max$) (publikacja nr 1, publikacja nr 2),

b) minutowy test pływacki na uwięzi kraulem na piersiach z pomiarem szczytowego pobór tlenu (VO_2peak) (publikacja nr 4).

Procedura wykonania testu stopniowanego w kanale przepływowym

Test przeprowadzany był w warunkach laboratoryjnych w kanale przepływowym AWF Kraków (Rycina 1). Wszyscy uczestnicy próby zostali poinformowani o procedurze i wykonali rozgrzewkę w wodzie podobną do stosowanej przed zawodami (1000 metrów, ze zmienną intensywnością). Na 24 godziny przed testem badani unikali intensywnego wysiłku fizycznego oraz stosowali standardową dietę w dniu badania.

Przed testem pływacy zakładali klips na nos aby oddychać tylko przez ustnik modułu oddechowego (Rycina 1) połączonego z analizatorem gazów oddechowych (Start2000 MES, Polska). Następnie przyjmowali pozycję poziomą na wodzie utrzymując głowę nad znacznikiem umieszczonym na dnie kanału w celu dostosowania ustawień aparatury do badanego i rozpoczynali minutowe swobodne pływanie w celu adaptacji do warunków testowych. Próbę rozpoczynał sygnał gwizdka (prędkość wyjściowa przepływu wody w kanale to 0,93 $m \cdot s^{-1}$), następnie co 2 minuty prędkość przepływu zwiększano o 0,06 $m \cdot s^{-1}$. Na bieżąco analizowano i zapisywano dane z analizatora gazów oddechowych (oddech za oddechem). Test był przeprowadzony do wolicjonalnej odmowy uczestnika i niemożności dalszego kontynuowania wysiłku. $\dot{V}O_2max$, progi wentylacyjne *AT* oraz *RCP* zostały wyznaczone na podstawie kryteriów zawartych w publikacjach: Beaver i wsp. (1986) i Karila i wsp. (2001). Wielkość $\dot{V}O_2max$ została wyznaczona ze średniej 30-sekundowego poboru tlenu z ostatnich sekund trwania testu. Określono również: czas trwania testu, prędkość pływania przy wystąpieniu progów *AT* (V_{AT}) i *RCP* (V_{RCP}) oraz $\dot{V}O_2max$ ($V_{\dot{V}O_2max}$). Określono także poziom wskaźników: *SL*, *SR* i *SI*.



Ryc 1. Uczestniczka badań podczas testu stopniowanego (źródło własne).

Przygotowanie zawodników do przeprowadzenia testu jednominutowego było takie samo jak do testu stopniowanego. Próbę przeprowadzono z użyciem tej samej aparatury oddechowej, ale była realizowana w wodzie stojącej w kanale przepływowym. Badany pływak był umocowany do uchwytu słupka startowego na nierozciągliwej stalowej linie połączonej z tekstylno-piankowym pasem umiejscowionym dookoła tułowia powyżej bioder, w talii pływaka. Przed rozpoczęciem testu każdy uczestnik wykonywał ok. 20 sekundowe pływanie kraulem na piersiach o niskiej intensywności w celu dostosowania się do warunków pomiaru. Rozpoczęcie i zakończenie testu odbywało się na sygnał gwizdka osoby kontrolującej czas i przebieg próby. Test wykonywany był z maksymalną intensywnością. Zebrane dane posłużyły do obliczenia następujących zmiennych:

1) średni pobór tlenu z pierwszych 30 sekund (1-30 $\dot{V}O_2$, $l \cdot min^{-1}$),
2) średni pobór tlenu z ostatnich 30 sekund (31-60 $\dot{V}O_2$, $l \cdot min^{-1}$),
3) średni pobór tlenu z ostatnich 20 sekund testu (41-60 $\dot{V}O_2$, $l \cdot min^{-1}$),
4) średni pobór tlenu z ostatnich 10 sekund testu (51-60 $\dot{V}O_2$, $l \cdot min^{-1}$) oraz
5) średni pobór tlenu z całego czasu trwania testu (1-60 $\dot{V}O_2$, $l \cdot min^{-1}$).

4.4. Pomiary funkcjonalne, wydolność anaerobowa, wskaźniki siły ciągu

Oceny siły mięśniowej dokonywano na podstawie wyników następujących prób:

1) 30-sekundowego testu pływania na uwięzi z maksymalną intensywnością,

2) 60-sekundowego testu pływania na uwięzi z maksymalną intensywnością (z pomiarem kinetyki poboru tlenu, opisywany powyżej),
3) wyskoku na platformie dynamometrycznej – Counter Movement Jump (CMJ)*,
4) 5 sekundowej pracy delfinowej nóg pod wodą na uwięzi.*

*zebrane dane nie zostały wykorzystane w publikacjach wchodzących w skład niniejszego cyklu.

Na potrzeby 30- i 60-sekundowego testu pływania na uwięzi uczestnikom przymocowano pas biodrowy i połączono ich stalową liną ze stalowym mocowaniem na wysokości 0,49 metra powyżej powierzchni wody. Częścią mocowania był bezprzewodowy siłomierz (ZPS5-BTU-1kN, Zbigniew Staniak, Polska) (o częstotliwości rejestracji 100Hz). W ramach testów zgromadzono następujące dane:

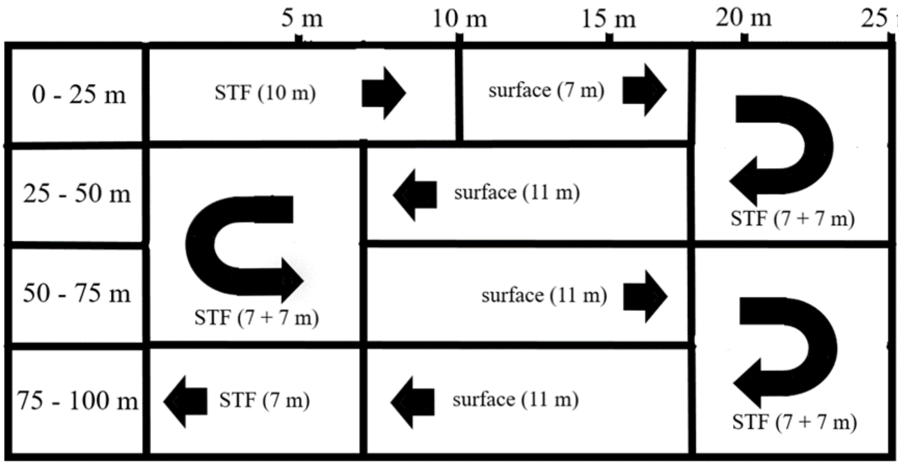
– siła maksymalna (F_{max}, N);
– średnia wartość siły z testu (F_{ave}, N);
– wskaźnik spadku siły ($F_{decline}$, N),
– średni popęd siły na cykl (I_{ave}[N · s]), definiowany jako całka siły dla wszystkich pełnych cykli ruchowych jakie wystąpiły w czasie 30 sekund rejestracji, podzielona przez liczbę pełnych cykli (*n*):

$$I_{ave} = \frac{\int_{t_0}^{t_1} F dt}{n},$$

gdzie: t_0 jest początkiem pierwszego pełnego cyklu a t_1 *to* zakończenie ostatniego cyklu.

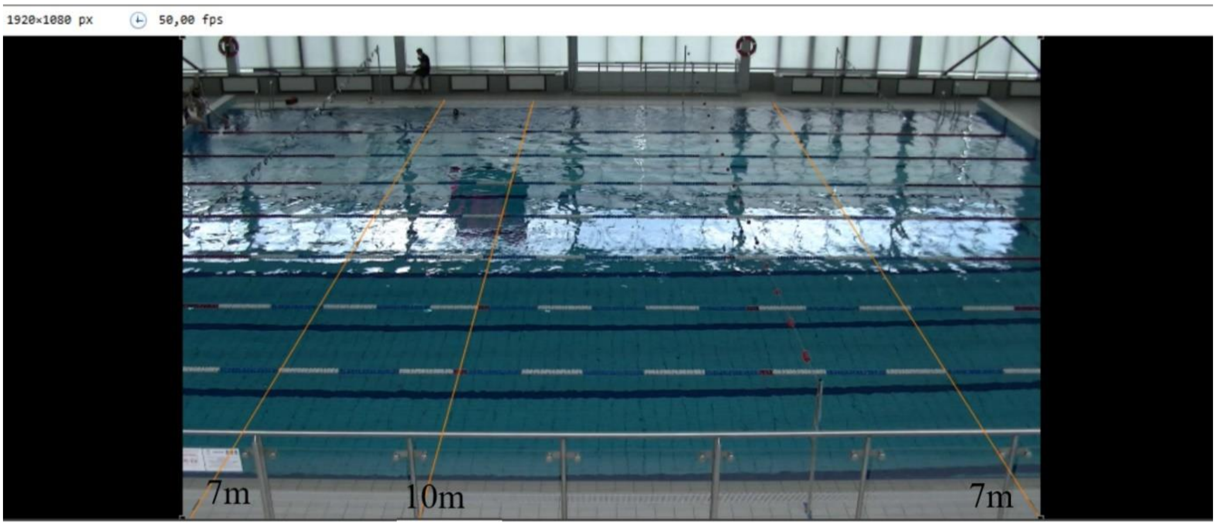
4.5. Sprawność pływacka w kraulu na piersiach - wyścigi

W badaniach przeprowadzono wyścigi pływackie na 25 metrowej pływalni zgodnie z przepisami Międzynarodowej Federacji Pływackiej (FINA – z fr. *Fédération Internationale de Natation* – obecnie *World Aquathics*) przy jednoczesnej rejestracji wideo wszystkich wyścigów oraz zastosowaniem elektronicznego pomiaru czasu (Omega, Szwajcaria). Przeprowadzono rejestracje wyścigów w kraulu na piersiach na dystansach: 50 m, 100 m, 200 m oraz 400 m. Wszyscy badani przemieszczali się techniką kraula na piersiach. Każda z rejestracji filmowych analizowana była z wydzieleniem stref pływalni: strefy startu, nawrotu/nawrotów, finiszu (STF z ang. start, turn, finish) oraz stref czystego pływania powierzchniowego (z ang. surface). Poniżej (Rycina 2) przedstawiono podział pokonywanego dystansu na strefy STF oraz surface na przykładzie dystansu 100 m.



Ryc 2. Podział wyścigu na dystansie 100 m na pływalni 25 metrowej z zaznaczeniem analizowanych stref startu, nawrotów i finiszu (STF) oraz czystego pływania powierzchniowego (surface). Rysunek własny na podstawie Kjendlie i wsp. 2006 oraz Wądrzyk 2021.

Rejestrację przeprowadzono z użyciem kamery (JVC GC-PX100BE, Japonia) z zastosowaniem trybu zapisu (klatkowania) 50 Hz i rozdzielczości klatki 1920x1080. Urządzenie było umieszczone na stabilnym statywie, w odległości 12,5 m od bocznej krawędzi basenu, ok. 7 m powyżej linii wody. Dzięki temu możliwe było zarejestrowanie przebiegu ruchu każdego badanego na dystansie ponad 11 m (7 m od ściany startowej i nawrotowej)



Ryc 3. Stopklatka z nagrania kamery usytuowanej na trybunach pływalni. Widoczne linie 7 i 10 metra poprowadzone od oznaczeń umieszczonych na brzegu pływalni.

Wspomniany wyżej podział na strefy skutkował takim ich udziałem w badanych dystansach:

a) 50 m: 32-m STF, 18-m surface;

b) 100 m: 59-m STF, 41-m surface;
c) 200 m: 115-m STF, 85-m surface;
d) 400 m: 227-m STF, 173-m surface.

Prędkości w strefach STF (V_{STF}) i surface ($V_{surface}$) były wyznaczone poprzez określenie czasu dzielącego przekroczenie dwóch wyimaginowanych linii pomiędzy znacznikami na brzegu basenu wyznaczającymi strefę przez głowę pływaka. Analizę wyścigów przeprowadzono w programie Kinovea (wersja 0.9.3).

Niewykorzystane w publikacjach dane dotyczące pływania w wyścigu na dystansie 50 m dziewcząt i chłopców a także 200 m, 400 m dziewcząt zostały przedstawione w aneksie.

Na potrzeby analizy kinematycznej techniki pływania zostały obliczone zmienne *SL*, *SR*, *SI*. Zmienne kinematyczne (*SL*, *SR* oraz *SI*) mierzone były w strefach czystego pływania (surface).

SR (cykl · min^{-1}) obliczano następująco:

$$SR = \frac{180}{t_3}$$

Gdzie t_3 to czas wykonania trzech cykli ruchowych ramion.

SL (m) była obliczana w przedstawiony niżej sposób:

$$SL = \frac{v}{SR}$$

gdzie *v* jest prędkością w strefie czystego pływania (V_{surf}).

SI uzyskano następująco:

$$SI\ (m^2 \cdot s^{-1}) = SL \cdot v$$

gdzie *v* jest prędkością w strefie czystego pływania (V_{surf}).

4.6. Postępowanie statystyczne

Wstępnego opracowania uzyskanych danych dokonano w programie Office Excel (Microsoft, 2016) tworząc zbiory dla dziewcząt i chłopców. Następnie eksportowano je do programu Statistica (Statsoft, wersja 13), z którego pomocą wykonano podstawową statystykę opisową. Szczegółowe przedstawienie postępowania statystycznego znajduje się w podrozdziałach im poświęconych, w każdym z artykułów zawartych w rozprawie.

4.7. Postępowanie metodyczne w procesie przygotowania poszczególnych publikacji

4.7.1. Pierwsza sesja badań

Grupa badawcza	19 dziewcząt (♀) i 19 chłopców (♂) wiek (lata): ♀ 13.4±0.26; ♂ 13.5±0.44 wysokość ciała (cm): ♀ 1.66±0.07; ♂ 1.68±0.08 masa ciała (kg):♀ 55.5±9.3; ♂ 56.9±10.6 punkty FINA (100 m kraul): ♀ 431.2±56; ♂ 354.2±50
Wykonywane pomiary	- test stopniowany w kanale badawczym (wyznaczanie progów metabolicznych AT i RCP, $\dot{V}O_2max$), - pływanie kraulem na uwięzi (30 sekund) w wodzie stojącej, - wyścig 100 i 400 m kraulem na piersiach z rejestracją wideo. - pomiary antropometryczne, określenie składu ciała, somatotypu, wieku biologicznego.
Sprzęt pomiarowy	- analizator gazów oddechowych (Start2000 MES, Polska) z oprogramowaniem (Ergo2000M MES, Polska), - siłomierz (ZPS5-BTU-1kN, Zbigniew Staniak, Polska) i oprogramowanie (MAX6v0M), - waga elektroniczna Tanita BC-418, - fałdomierz zegarowy, - taśma antropometryczna, - antropometr Sieber Hegner Maschinen AG, - zestaw do automatycznego pomiaru czasu (Omega, Szwajcaria), - kamera (JVC GC-PX100BE, Japonia) oraz statyw.
Zmienne	- pobór tlenu oraz prędkość na progach AT, RCP oraz $\dot{V}O_2max$, - maksymalna siła ciągu, średnia siła ciągu, wskaźnik spadku siły ciągu, średni impuls siły na cykl,

	- prędkość całkowita na dystansie, prędkość w strefie startu, nawrotów i finiszu (STF), prędkość czystego pływania kraulem na piersiach (surface) na dystansach 100 i 400 m, - wysokość ciała, masa ciała, skład ciała, somatotyp, wiek biologiczny, prognozowana wysokość ciała.
Analiza statystyczna	**Publikacja 1** - test Shapiro-Wilksa, - jednoczynnikowy test ANOVA z powtarzanymi pomiarami, - test Tukeya, - analiza rzetelności pomiarowej - ICC (*Intra-class correlation coefficient*), - korelacje r-Pearsona, - analiza mediacyjna testem Sobela. **Publikacja 2** - korelacje cząstkowe z kontrolą zmiennej *BA*, - określenie trendu: np.: kwadratowego, wykładniczego **Publikacja 3** - korelacje cząstkowe z kontrolą zmiennej *BA*

4.7.2. Druga sesja badań

Grupa badawcza	41 dziewcząt (♀) i 51 chłopców (♂) wiek (lata): ♀ 13.5±0.85; ♂ 13.5±0.9 wysokość ciała (cm): ♀ 1.65±0.06; ♂ 1.69±0.08 masa ciała (kg):♀ 53.2±6.8; ♂ 58±10 punkty FINA (200 m kraul): ♀ 416.42±73.04 ♂ 350.32 ± 60.22
Wykonane pomiary	- pływanie kraulem na uwięzi (20 sekund) w wodzie stojącej, - pływanie kraulem na uwięzi (60 sekund) w wodzie stojącej, z pomiarem kinetyki poboru tlenu (VO_2peak), - wyścig 100 i 400 m kraulem na piersiach z rejestracją wideo, - test CMJ, - 5 sekundowy test kopnięć delfinowych w zanurzeniu, - pomiary antropometryczne, określenie składu ciała, somatotypu, wieku biologicznego
Sprzęt pomiarowy	- analizator gazów oddechowych (Start2000 MES, Polska) z oprogramowaniem (Ergo2000M MES, Polska), - siłomierz (ZPS5-BTU-1kN, Zbigniew Staniak, Polska) i oprogramowanie MAX6v0M, - waga elektroniczna Tanita BC-418, - fałdomierz zegarowy, - taśma antropometryczna,

	- antropometr Sieber Hegner Maschinen AG, - zestaw do automatycznego pomiaru czasu (Omega, Szwajcaria), - kamera (JVC GC-PX100BE, Japonia).
Zmienne	**Publikacja 4** - szczytowy pobór tlenu (VO_2peak) i kinetyka poboru tlenu, - maksymalna siła, średnia siła ciągu, średni impuls siły na cykl, - prędkość całkowita na dystansie, prędkość w strefie startu, nawrotów i finiszu (STF), prędkość czystego pływania (surface) na dystansach 50, 200 m kraulem na piersiach, - wysokość ciała, masa ciała, skład ciała, somatotyp, wiek biologiczny, prognozowana wysokość ciała,
Analiza statystyczna	- określenie trendu: np.: kwadratowego, wykładniczego dla ukształtowania zmiennych kinematycznych pływania, - korelacje cząstkowe z kontrolą zmiennej *BA*.

5. Wyniki oraz konkluzje poszczególnych artykułów

5.1. Publikacja nr 1

Głównym celem publikacji była ocena współzależności pomiędzy wskaźnikami wydolności krążeniowo-oddechowej, wydolności anaerobowej mierzonymi w pływaniu na uwięzi, składem ciała i kinematyką pływania a *BA* zawodniczek. Ponadto, badano zmiany wskaźników kinematycznych związanych z techniką pływania na rezultaty w wyścigu na dystansie 100 metrów kraulem na piersiach przy jednoczesnej kontroli wpływu *BA* na obserwowane zależności.

W badaniach stanowiących podstawę do przygotowania artykułu wzięło udział 19 dziewcząt (13.4±0.26 lat). Sprawność pływacką określała prędkość przepłynięcia 100 m kraulem na piersiach. Zawodniczki prezentowały na tym dystansie poziom sportowy określony na 431.2±56 punktów FINA.

W ramach analizy statystycznej stwierdzono następujące zależności pomiędzy zmiennymi:

a) wiek biologiczny był skorelowany z beztłuszczową masą ciała (*FFM*), całkowitą masą wody (*TBW*), wysokością i masą ciała oraz szacowaną całkowitą masą mięśni,
b) wiek biologiczny, wysokość ciała, masa ciała, całkowita szacowana masa mięśni, masa mięśni ramion, tułowia i kończyn dolnych prezentowały silny związek ze zmiennymi testu pływania na uwięzi,
c) zmienne: $\dot{V}O_2max$, intensywność na poziomie progów metabolicznych *AT*, *RCP* była wysoko i bardzo wysoko skorelowana ze wskaźnikami antropometrycznymi, składem ciała, wiekiem biologicznym,
d) prędkość pływania uzyskana przy wystąpieniu *AT* i *RCP* oraz $\dot{V}O_2max$, była średnio, silnie lub bardzo silnie skorelowana z prędkością pływania na dystansie 100-m kraulem na piersiach,
e) wskaźniki kinematyczne: *SL* oraz *SI* były silnie lub bardzo silnie skorelowane ze wskaźnikami prędkości pływania na dystansie 100 m kraulem na piersiach,
f) analiza mediacji wykonana z udziałem wskaźników najsilniej skorelowanych z prędkością pływania na 100-m kraulem na piersiach (V_{AT}, V_{RCP}, $V_{\dot{V}O_2max}$, *SL*, *SI*) wykazała, że wiek biologiczny nie wpływał istotnie na zależności pomiędzy

tymi zmiennymi podlegającymi kształtowaniu w treningu sportowym, a rezultatami wyścigu.

W niniejszym artykule zidentyfikowano dwie grupy zmiennych silnie związanych ze sprawnością młodych pływaczek w wyścigu na dystansie 100-m kraulem na piersiach: wytrzymałościowe, związane z wytrenowaniem pływackim: V_{AT}, V_{RCP}, $V_{\dot{V}O_2max}$, podobnie jak zmienne kinematyczne, modelowane w treningu na co dzień (*SL* i *SI*). Zmienne te nie były istotnie powiązane z *BA*. Głównym wnioskiem wspomnianej pracy było to, iż wynik młodych zawodniczek zależy od wytrenowanych fizjologicznych właściwości oraz efektywnej techniki ruchów pływackich, a mniej od możliwości siłowych i budowy somatycznej.

5.2. Publikacja nr 2

Celem badania było określenie wpływu wysiłkowych zmiennych fizjologicznych mierzonych w warunkach pływania oraz zmiennych kinematycznych techniki pływania młodych zawodników na wyniki sportowe w kraulu na piersiach w wyścigu na dystansie 400 metrów.

W badaniach stanowiących podstawę do przygotowania artykułu wzięło udział 19 chłopców (13.5±0.44 lat). Sprawność pływacką określała prędkość przepłynięcia 400 m kraulem na piersiach. Zawodnicy prezentowali na tym dystansie poziom sportowy obliczony na 352 punkty FINA.

W ramach analizy statystycznej stwierdzono następujące zależności pomiędzy zmiennymi:

1) odnotowano średnie i wysokie korelacje pomiędzy prędkością pływania w wyścigu a prędkością przepływu odpowiadającą chwili osiągnięcia przez badanego progu *AT* i $\dot{V}O_2max$,
2) zmienne $\dot{V}O_2max$ oraz pobór tlenu na progach *AT* i *RCP* były silnie lub bardzo silnie skorelowane z *BA*,
3) zmienne kinematyczne *SL* i *SI* były silnie powiązane z *BA*, natomiast $V_{surface}$ była silnie zależna statystycznie z *SI*, pomimo kontroli czynnika *BA*,
4) zaobserwowano średnie i silne korelacje cząstkowe z kontrolą *BA* pomiędzy *SR* z pierwszego, przedostatniego i ostatniego odcinka 50 metrowego a prędkością pływania na tych odcinkach w wyścigu na 400 metrów. *SI* na

każdym, za wyjątkiem drugiego odcinka 50 metrowego, było powiązane z $V_{surface}$ na poszczególnych odcinkach.

Ustalono, że osiągane prędkości V_{AT}, V_{vo2max} istotnie determinują poziom sportowy i efektywność techniki w kraulu na piersiach młodych zawodników w wyścigu na dystansie 400-m. Zaobserwowano silny wpływ wieku biologicznego na poziom maksymalnego poboru tlenu, poboru tlenu na progach *AT* i *RCP* oraz na wskaźniki kinematyczne: *SR*, *SL*, *SI*. Stwierdzono powiązanie pomiędzy poziomem wydolności aerobowej u chłopców trenujących pływanie a zdolnością utrzymania efektywnej techniki pływania w wyścigu na dystansie 400-m kraulem na piersiach.

5.3. Publikacja nr 3

Celem badań było poszukiwanie zależności zmiennych wyścigu na dystansie 100 metrów kraulem na piersiach chłopców i zmiennych morfologicznych tj. składu tkankowego ciała, wymiarów antropometrycznych oraz siły w pływaniu na uwięzi. W badaniach tych obliczono, również wskaźniki kinematyczne wskaźniki techniki pływackiej.

W materiale stanowiącym podstawę do przygotowania artykułu wzięło udział 19 chłopców (13.5±0.44 lat). Sprawność pływacką określała prędkość przepłynięcia wyścigu 100 m kraulem na piersiach. Zawodnicy prezentowali w tej konkurencji poziom sportowy obliczony na 354.18±49.74 punktów FINA.

Zaobserwowano:

1) dodatnie, istotnie statystyczne zależności pomiędzy masą ciała a średnią siłą ciągu pływaków podczas testu na uwięzi. Korelacje dostrzeżono także pomiędzy szacowaną masą mięśniową ramion, tułowia, kończyn dolnych a siłą maksymalną, średnią oraz średnim impulsem siły na cykl w pływaniu na uwięzi. Zależności te były uzyskane w obliczeniach z kontrolą zmiennej ubocznej - *BA*,
2) istotną inter-korelację (korelacja cząstkowa z kontrolą *BA*) siły średniej osiągniętą w pływaniu na uwięzi z prędkością pływania wyścigu 100 m kraulem na piersiach,
3) istotną zależność *SL* i *SI* wyścigu pływackiego ze wskaźnikiem średniego popędu siły na cykl w pływaniu na uwięzi.

Odnotowano silną zależność wskaźników masy mięśniowej ciała, masy mięśniowej poszczególnych segmentów ciała z średnią siły pływania na uwięzi. Z kolei średnia siła pływania na uwięzi determinowała prędkość pływania 100 m kraulem na piersiach. Wywnioskowano, że zdolność wykonywania efektywnych pociągnięć (średni popęd siły na cykl) warunkuje efektywność techniki wyrażoną poprzez *SI*, a dalej przekłada się to przy wyższym poziomie wskaźnika na osiąganie większej prędkości pływania wyścigu na 100 m.

5.4. Publikacja nr 4

Rozważania dotyczą kinetyki poboru tlenu, zdolności do wytwarzania siły napędowej w teście jednominutowym na uwięzi oraz morfologicznych wskaźników wysokiej sprawności pływackiej młodych zawodników.

W badaniach wzięło udział 48 chłopców (13.5±0.9 lat). Sprawność pływacką określała prędkość przepłynięcia wyścigu 200-m kraulem na piersiach. Uczestnicy prezentowali poziom sportowy równy 350.32±60.22 punktom FINA.

Analiza statystyczna pozwoliła na dokonanie następujących stwierdzeń:

1) wzrost poboru tlenu w teście przybrał trend liniowy, przyjmując najwyższe wartości dla średniej w ostatnich 10 sekund testu,
2) pobór tlenu uzyskany w teście minutowym (*31-60* $\dot{V}O_2$, *41-60* $\dot{V}O_2$, *51-60* $\dot{V}O_2$) był średnio lub silnie skorelowane z wytwarzaniem siłą maksymalnej, siły średniej oraz średnim impulsem siły w pływaniu na uwięzi,
3) pobór tlenu (*41-60* $\dot{V}O_2$, *51-60* $\dot{V}O_2$) był przeciętnie lub silnie skorelowany z prędkością pływania wyścigu na 200 m kraulem na piersiach oraz z *SI* w tym wyścigu. Ponadto, wykazano istotną zależność pomiędzy *51-60* $\dot{V}O_2$ a *SL*,
4) spośród wskaźników charakteryzujących technikę pływania pozytywne korelacje zaobserwowano pomiędzy *SL*, *SI* oraz prędkością pływania,
5) przeciętny poziom związku korelacyjnego zaobserwowano pomiędzy wskaźnikami pływania na uwięzi (F_{max}, F_{ave}, I_{ave}) a rezultatami wyścigu pływackiego na 200 m,
6) wykazano korelacje pomiędzy kinetyką poboru tlenu, a wskaźnikami siły ciągu i techniki pływania (*SL*, *SI*), także rezultatami pływackimi. Zależności te współgrały z wyższym *BA*.

Młodzi zawodnicy posiadający zdolność do wcześniejszego osiągania wysokiego poziomu poboru $\dot{V}O_2$ mają możliwość osiągnąć wcześniej wyższe tempo wyścigu na dystansach średnich. Dynamika 1-minutowego $\dot{V}O_2$ zmierzona w badaniach okazała się dobrym, istotnym wskaźnikiem oceny sprawności pływackich na dystansie średnim (200 m). Wysoka dynamika $\dot{V}O_2$ była istotnie zależna ze zdolnościami siłowymi w pływaniu na uwięzi i wysoką prędkością pływania wyścigu. Wysoki poziom $\dot{V}O_2$ jest kluczowy dla utrzymania odpowiedniej siły pociągnięć oraz techniki pływackiej w kraulu na piersiach.

6. Wnioski

W niniejszych obserwacjach *BA* wykazywał większą zmienność w odniesieniu do wieku kalendarzowego badanych sportowców i wpływał na wyższy poziom wskaźników budowy somatycznej oraz właściwości fizjologicznych w grupach badanych dziewcząt i chłopców. Zaobserwowano wysokie korelacje zmiennych somatycznych, fizjologicznych z wiekiem biologicznym (publikacja nr 1 i 2). Wspomniane różnice w dużej części odpowiadają za różnice w sprawności pływackiej badanych w wyścigach na dystansach krótkich (publikacja nr 1) oraz średnich (publikacja nr 2 i 4). Analiza mediacji z udziałem *BA* (publikacji nr 1) okazała się być wartościowym narzędziem w identyfikacji zmiennych wyjaśniających sprawność pływacką. Korelacje cząstkowe z kontrolą *BA* (publikacje nr 2, 3, 4) pozwoliły na wskazanie większej liczby zmiennych, które silnie korelowały ze sprawnością pływacką mimo zróżnicowania *BA* w grupach badanych grup.

Zmienne antropometryczne istotnie determinowały: pobór tlenu w poszczególnych przedziałach czasowych oraz wskaźniki testu pływania na uwięzi. Zarówno u dziewcząt jak i chłopców przy braku kontroli wieku biologicznego obserwujemy silną zależność wartości poboru tlenu i zmiennych antropometrycznych. W przypadku dziewcząt (publikacja nr 1) i chłopców (publikacja nr 3) średnia siła i popęd siły na cykl jest najbardziej powiązany z szacowaną masą mięśniową tułowia, która może stanowić obraz całościowej muskulatury pływaka.

Poziom zdolności wytrzymałościowych badanych zawodników określony wielkością poboru tlenu na progach metabolicznych *AT*, RCP oraz na poziomie maksymalnym ($\dot{V}O_2$max) mierzonych w teście stopniowanym same w sobie nie stanowią podstawy osiągania wysokich wyników w wyścigach na dystansach krótkich (publikacja nr 1) i średnich (publikacja nr 2 i 4). Może to potwierdzać brak istotnych statystycznie zależności pomiędzy poborem tlenu w teście stopniowanym z prędkością pływania. Dopiero prędkości na poziomie progów wentylacyjnych oraz przy maksymalnym poborze tlenu były zbieżne z wysoką prędkością pływania. Istotna zależność wieku biologicznego z odnotowanymi dużymi wielkościami poboru tlenu potwierdza, iż proces dojrzewania jest powiązany z rozwojem tlenowego systemu wytwarzania energii. Zdolność szybkiego aktywowania przemian tlenowych w wytwarzanie energii okazała się silnie determinować sprawność pływacką na dystansach średnich. Najwyższy wzrost poboru tlenu w teście minutowym u badanych pływaków odnotowano po 30 sekundzie wysiłku.

Zaobserwowano mocny związek wskaźników siły pływania na uwięzi i prędkości pływania na dystansach krótkich (publikacja nr 3) oraz średnich (publikacja nr 4). Nie zawsze, jednak zależność taka istniała w podjętych obserwacjach, szczególnie u dziewcząt. Rozważono, iż wśród badanych dziewcząt zaawansowanie techniczne a nie przewaga somatyczna czy zdolności siłowe mogą odpowiadać za wyższą sprawnością pływacką (publikacja nr 1). Wśród wskaźników zebranych w testach pływania na uwięzi najsilniejszy wpływ na osiągnięcia pływackie miały: a) siła średnia, b) średni popęd siły na cykl (publikacja nr 3 i 4). Można stwierdzić, że siła średnia osiągana w teście pływania na uwięzi stanowi obraz sprawności glikolitycznego systemu wytwarzania energii w połączeniu umiejętnością wykonywania efektywnych ruchów pływackich wytwarzających siłę ciągu. Średni popęd siły na cykl był istotnym wskaźnikiem oceny efektywności techniki i rezultatów pływackich. Siła mięśni mierzona z użyciem próby specjalistycznej (pływanie na uwięzi) jest silnie powiązana z szerokim zestawem zmiennych morfologicznych w przypadku dziewcząt (publikacja nr 1) jak i chłopców (publikacja nr 3). Należy nadmienić, że zawodnicy bardziej zaawansowani w rozwoju biologicznym, dysponujący większymi zdolnościami siłowymi mają za tą przyczyną większe szanse na osiągnięcie wysokich wyników w porównaniu do ich mniej dojrzałych biologicznie rówieśników.

W przedstawionych obserwacjach odnotowywano wyższy poziom wskaźników kinematycznych techniki pływania (*SL* i *SI*) wraz większymi rozmiarami ciała jak rozpiętość ramion, całkowita długość ciała. Wielkość wskaźników kinematycznych oraz prędkość pływania zwiększały się odpowiednio wraz z wiekiem biologicznym (publikacja nr 4). Powinno się jednak zwrócić uwagę, że wysoki poziom wskaźników kinematycznych pływania (*SL* i *SI* może być wynikiem intensywnej pracy treningowej zawodnika na tym polu. Potwierdzają to wyniki publikacji nr 1, gdzie nie wykazano istotnego wpływu wieku biologicznego na wartości *SL*, *SI* u dziewcząt. Rozważania nad kinematyką podjęte w publikacji nr 2 pozwalają stwierdzić, iż wartości wskaźników kinematycznych rozpatrywane dla poszczególnych odcinków danego dystansu (w tym wypadku 400-m) mogą umożliwić szersze wnioskowanie. Dostrzeżono, iż ich zmiany, które można łączyć z poziomem wytrenowania, są powiązane z taktyką rozkładu tempa pływania w wyścigu. Potwierdzono, że *SL* wykazuje stały spadek na dystansie a czynnikiem pozwalającym manipulować prędkością w ramach postępującego zmęczenia jest zdolność utrzymania wysokiego *SR*, a nawet jego wzrostu po spadku w środkowej części wyścigu, na ostatnich 100 metrach z 400.

W toku badań stwierdzono silne zróżnicowanie *BA* pływaków 12-15 letnich. Przyczynia się to do silnego determinowania wyników w tym przedziale wiekowym przez między innymi wpływ na: wymiary długościowe, poziom wydolności aerobowej, większą muskulaturę i przez to większe zdolności siłowe. Jednocześnie wykazano, że wspomniane różnice pomiędzy zawodnikami późno i wczesnorozwojowymi biologicznie mogą być częściowo zniwelowane poziomem przygotowania technicznego. Autor uważa, że wspomniane obserwacje powinny być przedmiotem zainteresowania trenerów i innych osób odpowiedzialnych za proces szkolenia i selekcji zawodników w ramach sportu pływackiego. Kluczowym dla pozyskania zawodników osiągających wysokie wyniki w wieku seniorskim jest zdaniem autora szczególna opieka nad rozwojem sportowym osób utalentowanych o normalnym i późnym tempie rozwoju biologicznego, przy jednoczesnej indywidualizacji treningu osób o rozwijających się biologicznie szybciej.

7. Ograniczenia rozprawy oraz dalsze kierunki badań

Pewnym ograniczeniem są odmienne w porównaniu do pływania swobodnego warunki przeprowadzenia niektórych testów pływackich. Autor rozprawy i współwykonawcy badań dołożyli wszelkich starań aby testy odzwierciedlały mechanikę i warunki środowiskowe (wodne) wysiłku pływackiego, natomiast zastosowanie: uwięzi, pływania w kanale przepływowym z rurką oddechową stanowiły pewnego rodzaju odmienność, rzadko trudność. Należy jednak nadmienić, że z podobnymi problemami mierzą się także inni badacze a wspomniane ograniczenia wynikają ze świadomego wyboru techniki i użytkowanej aparatury badawczej. Autor uważa jednak, że umożliwienie zawodnikom wstępnej adaptacji do warunków przeprowadzanych testów wpłynęło pozytywnie na jakość-rzetelność wykonania badań.

W przedstawionych publikacjach przedstawiono dużą część zebranych w toku badań wyników. Funkcjonujący obecnie system i czas przygotowania publikacji, chęć zainteresowania redakcji czasopism, a dalej odbiorców innowacyjnymi, ciekawymi wynikami powoduje dużą pracochłonność. Autor ma zamiar dalszego wykorzystania części nieopublikowanych dotąd danych dotyczących np. wyników nowatorskiego 5-sekundowego testu ruchów delfinowych w zanurzeniu.

Autor niniejszej dysertacji doktorskiej planuje kontynuowanie pracy badawczej wraz z pracownikami naukowo-badawczymi AWF Kraków – publikowanie naukowe oraz dzielenie się praktycznymi wnioskami z trenerami i zawodnikami Małopolskiego Okręgowego Związku Pływackiego. Przeprowadzone badania wskazują na dalszą możliwość ich kontynowania z przeprowadzeniem dalszych bardziej pogłębionych analiz w zakresie metabolizmu energetycznego, budowy morfologicznej oraz techniki pływania z wykorzystaniem posiadanej oraz nowszej aparatury badawczej.

Część II

Dokumenty źródłowe oraz dodatki

Piśmiennictwo

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Aneks

Średnia prędkość pływania: całkowita (V_{total}), w strefie pływania powierzchniowego ($V_{surface}$), w strefie startu, nawrotów oraz finiszu (V_{STF}) pochodzące z niewykorzystanych danych dotyczących pływania w wyścigach na dystansach: 50 m, 200 m i 400 m kraulem na piersiach.

	V_{total}	$V_{surface}$	V_{STF}
50 m ♀	1.62±0.09	1.52±0.07	1.69±0.10
50 m ♂	1.72±0.11	1.61±0.10	1.79±0.12
200 m ♀	1.35±0.08	1.28±0.08	1.41±0.09
400 m ♀	1.30±0.06	1.23±0.07	1.35±0.07

Średnie wartości *SR, SL* oraz *SI* uzyskane z niewykorzystanych danych dotyczących pływania w wyścigach na dystansach: 50 m, 200 m i 400 m kraulem na piersiach.

	SR	*SL*	*SI*
50 m ♀	52.41±4.06	1.75±0.14	2.68±0.28
50 m ♂	55.44±4.67	1.75±0.16	2.86±0.36
200 m ♀	40.21±4.00	1.91±0.18	2.41±0.29
400 m ♀	37.72±3.77	1.97±0.18	2.42±0.26

Streszczenie

Sprawność pływacka młodych zawodników w kraulu na piersiach jest determinowana przez szereg zmiennych fizjologicznych, antropometrycznych, kinematycznych. Określono, że są to między innymi: poziom szczytowego poboru tlenu, prędkość pływania na poziomie progów wentylacyjnych *AT*, *RCP* i prędkość odpowiadająca osiągnięciu $\dot{V}O_2max$, ponadto siła średnia średni popęd siły w pływaniu na uwięzi wskaźniki kinematyczne pływania - *SL*, *SI*, i somatyczne (wysokość i masa ciała, całkowita masa mięśniowa, beztłuszczowa masa ciała).

Wiek biologiczny (*BA*) determinował poziom zdolności siłowych, wydolność aerobową oraz właściwości somatyczne. Odseparowanie wpływu *BA* poprzez zastosowanie m.in. korelacji cząstkowych z kontrolą czynnika *BA*, pozwoliło na bardziej obiektywną identyfikację zmiennych determinujących sprawność pływacką.

Na podstawie przeprowadzonych badań stwierdza się, że sprawność pływacka młodych zawodników na dystansach krótkich (100 m) w kraulu na piersiach jest powiązana z: efektywną techniką (*SL*, *SI*), prędkością pływania osiąganą na progach *AT* oraz *RCP* oraz siłą średnią pływania na uwięzi.

W przypadku wyścigów rozgrywanych na średnim dystansie (200 m) wysoka prędkość pływania była połączona z wysokimi wartościami: poboru tlenu, siły średniej, siły maksymalnej, średniego popędu siły w pływaniu na uwięzi, a także z *SL* i *SI*. Rezultaty wyścigu pływania 400 m były silnie powiązane z poziomem wskaźników fizjologicznych, kinematycznych mierzonych podczas testów laboratoryjnych i w wyścigach pływackich.

Niniejsze obserwacje pozwalają stwierdzić, że trening młodych zawodników i dobór do kolejnych etapów szkolenia powinny być poparte oceną zaawansowania zmian rozwojowych. Pozwoli to na bardziej trafne, zindywidualizowane, postępowanie treningowe.

Abstract

The sports performance of young competitors in the front crawl stroke is determined by a number of physiological, kinematic and anthropometric variables. It has been established that these are, among others: the level of peak oxygen uptake, swimming speed at *AT*, *RCP* ventilatory thresholds and at maximum oxygen uptake, average strength and average propelling force in tethered swimming, length of the swimming cycle, as well as swimming technique efficiency index, and anthropometric variables, i.e.: body height and mass, estimated body muscle mass or lean body mass.

BA turned out to significantly determine strength level, as well as oxygen and anthropometric variables. Excluding the impact of diversity regarding biological maturity by using, e.g. partial correlations with the control of the *BA* factor, allowed for partial identification of variables explaining swimming efficiency and, at the same time, those independent of biological development level.

Based on the conducted research, it may be concluded that the swimming efficacy of young swimmers over short distances (100 m) in front crawl technique is related to: effective technique (*SL*, *SI*), swimming speed obtained at *AT* and *RCP* thresholds and average strength in tethered swimming.

In the case of medium distances (200 m), high swimming speed was combined with high values of: oxygen uptake in the minute test, average and maximum strength, average propelling force in tethered swimming, as well as *SL* and *SI*. The 400 m distance was strongly associated with physiological and kinematic indices determining efficacy of the swimming effort.

The undertaken observations allow to make the conclusion that the training of young swimmers and the selection for subsequent stages of training must be supported by the observation concerning advancement of developmental changes. This will allow for implementation of more individualized, accurate training procedure.

Lista załączników

- zaświadczenia o udziale autorskim
- zgoda Komisji Bioetycznej na realizację badań
- artykuły naukowe stanowiące cykl publikacji

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OŚWIADCZENIE PIERWSZEGO AUTORA

Mój udział w przygotowaniu publikacji pt. Biological Age in Relation to Somatic, Physiological, and Swimming Kinematic Indices as Predictors of 100 m Front Crawl Performance in Young Female Swimmers (International Journal of Environmental Research and Human Health - DOI: 10.3390/ijerph18116062) obejmował:

- sformułowanie problem badawczego,

- zaplanowanie i przeprowadzenie pomiarów,

- opracowanie wyników oraz analizę statystyczną,

- konsultacje przy przygotowaniu wstępnej wersji manuskryptu oraz zaakceptowanie jego ostatecznej wersji.

Oświadczam, że mój udział wkładu pracy w powstanie artykułu wyniósl 55%.

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- pomoc w wykonaniu pomiarów,

- konsultacje przy przygotowaniu wstępnej wersji manuskryptu oraz zaakceptowanie jego ostatecznej wersji.

Oświadczam, że mój udział wkładu pracy w powstanie artykułu wyniósł 10%.

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- konsultacje przy przygotowaniu wstępnej wersji manuskryptu oraz zaakceptowanie jego ostatecznej wersji,

- analizę statystyczną.

Oświadczam, że mój udział wkładu pracy w powstanie artykułu wyniósł 10%.

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- przeprowadzenie pomiarów antropometrycznych,
- zaakceptowanie ostatecznej wersji manuskryptu.

Oświadczam, że mój udział wkładu pracy w powstanie artykułu wyniósł 5%.

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- konsultacje przy przygotowaniu wstępnej wersji manuskryptu oraz zaakceptowanie jego ostatecznej wersji.

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- konsultacje przy przygotowaniu wstępnej wersji manuskryptu oraz zaakceptowanie jego ostatecznej wersji.

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I confirm that my participation in preparing the article entitled: Biological Age in Relation to Somatic, Physiological, and Swimming Kinematic Indices as Predictors of 100 m Front Crawl Performance in Young Female Swimmers (International Journal of Environmental Research and Human Health - DOI: 10.3390/ijerph18116062) included:

- consultations refering to initial version of manuscript and acceptance of its final form.

My participation on the preparation of the manuscript could be estimated as **5%** of all the work.

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- consultations refering to initial version of manuscript and acceptance of its final form.

My participation on the preparation of the manuscript could be estimated as **5%** of all the work.

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OŚWIADCZENIE PIERWSZEGO AUTORA

Mój udział w przygotowaniu publikacji pt. Study of talented young male swimmers–scientific approach to the kinematic and physiological predictors of 400-m front crawl race (*ACTA OF BIOENGINEERING AND BIOMECHANICS*, 2022, 24.1. DOI: 10.37190/ABB-01964-2021-02) obejmował:

- sformułowanie problem badawczego,

- zaplanowanie i przeprowadzenie pomiarów,

- opracowanie wyników oraz analizę statystyczną,

- konsultacje przy przygotowaniu wstępnej wersji manuskryptu oraz zaakceptowanie jego ostatecznej wersji.

Oświadczam, że mój udział wkładu pracy w powstanie artykułu wyniósł 80%.

Kamil Sokołowski
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OŚWIADCZENIE WSPÓŁAUTORA

Mój udział w przygotowaniu publikacji pt. Study of talented young male swimmers–scientific approach to the kinematic and physiological predictors of 400-m front crawl race (*ACTA OF BIOENGINEERING AND BIOMECHANICS*, 2022, 24.1. DOI: 10.37190/ABB-01964-2021-02) obejmował:

- przeprowadzenie pomiarów,

- konsultacje przy przygotowaniu wstępnej wersji manuskryptu oraz zaakceptowanie jego ostatecznej wersji.

Oświadczam, że mój udział wkładu pracy w powstanie artykułu wyniósł 15%.

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OŚWIADCZENIE WSPÓŁAUTORA

Mój udział w przygotowaniu publikacji pt. Study of talented young male swimmers- scientific approach to the kinematic and physiological predictors of 400-m front crawl race (*ACTA OF BIOENGINEERING AND BIOMECHANICS*, 2022, 24.1. DOI: 10.37190/ABB-01964-2021-02) obejmował:

- przeprowadzenie pomiarów antropometrycznych.

Oświadczam, że mój udział wkładu pracy w powstanie artykułu wyniósł 5%.

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Wydział Wychowania Fizycznego
Instytut Sportu
Zakład Sportów Wodnych

Kraków, 07.02.2023

OŚWIADCZENIE PIERWSZEGO AUTORA

Mój udział w przygotowaniu publikacji pt. Body composition and anthropometrics of young swimmers in relation to the tethered swimming and kinematics of 100-m front crawl race (International Journal of Sports Medicine and Physical Fitness- DOI:10.23736/S0022-4707.22.14054-5) obejmował:

- sformułowanie problem badawczego,

- zaplanowanie i przeprowadzenie pomiarów,

- opracowanie wyników oraz analizę statystyczną,

- konsultacje przy przygotowaniu wstępnej wersji manuskryptu oraz zaakceptowanie jego ostatecznej wersji.

Oświadczam, że mój udział wkładu pracy w powstanie artykułu wyniósł 85%.

....

Podpis

Potwierdzenie promotora:

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Instytut Sportu
Zakład Sportów Wodnych

Kraków, 07.12.2022

OŚWIADCZENIE WSPÓŁAUTORA

Mój udział w przygotowaniu publikacji pt. Body composition and anthropometrics of young swimmers in relation to the tethered swimming and kinematics of 100-m front crawl race (International Journal of Sports Medicine and Physical Fitness- DOI:10.23736/S0022-4707.22.14054-5) obejmował:

- pomoc w wykonaniu pomiarów,

- konsultacje przy przygotowaniu wstępnej wersji manuskryptu oraz zaakceptowanie jego ostatecznej wersji.

Oświadczam, że mój udział wkładu pracy w powstanie artykułu wyniósł 10%.

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Podpis

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OŚWIADCZENIE WSPÓŁAUTORA

Mój udział w przygotowaniu publikacji pt. Body composition and anthropometrics of young swimmers in relation to the tethered swimming and kinematics of 100-m front crawl race (International Journal of Sports Medicine and Physical Fitness- DOI:10.23736/S0022-4707.22.14054-5) obejmował:

- konsultacje przy przygotowaniu wstępnej wersji manuskryptu oraz zaakceptowanie jego ostatecznej wersji.

Oświadczam, że mój udział wkładu pracy w powstanie artykułu wyniósł 5%.

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Kraków, 07.02.2023

OŚWIADCZENIE PIERWSZEGO AUTORA

Mój udział w przygotowaniu publikacji pt. VO2 kinetics and tethered strength influence the 200-m front crawl stroke kinematics and speed in young male swimmers (Frontiers in Physiology, DOI: 10.3389/fphys.2022.1045178) obejmował:

- sformułowanie problem badawczego,

- zaplanowanie i przeprowadzenie pomiarów,

- opracowanie wyników oraz analizę statystyczną,

- konsultacje przy przygotowaniu wstępnej wersji manuskryptu oraz zaakceptowanie jego ostatecznej wersji.

Oświadczam, że mój udział wkładu pracy w powstanie artykułu wyniósł 70%.

Kamil Sokołowski
....

Podpis

Potwierdzenie promotora:

Dr hab. Marek Strzała, prof. AWF

17.11.2022

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School of Education,
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Co-authors' contribution statement

I confirm that my participation in preparing the article entitled: VO2 kinetics and tethered strength influence the 200-m front crawl stroke kinematics and speed in young male swimmers (Frontiers in Physiology, DOI: 10.3389/fphys.2022.1045178) included:

- consultations referring to initial version of manuscript and acceptance of its final form.

My participation on the preparation of the manuscript could be estimated as **5%** of all the work

Signature

Raul Filipe Barbosa Bartolomeu

(Raul Filipe Barbosa Bartolomeu)

17.11.2022

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Co-authors' contribution statement

I confirm that my participation in preparing the article entitled: VO2 kinetics and tethered strength influence the 200-m front crawl stroke kinematics and speed in young male swimmers (Frontiers in Physiology, DOI: 10.3389/fphys.2022.1045178) included:

- consultations refering to initial version of manuscript and acceptance of its final form.

My participation on the preparation of the manuscript could be estimated as **5%** of all the work

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Signature

dr hab. Marek Strzała, prof. AWF
Akademia Wychowania Fizycznego
im. Bronisława Czecha w Krakowie
Wydział Wychowania Fizycznego
Instytut Sportu
Zakład Sportów Wodnych

Kraków, 17.11.2022

OŚWIADCZENIE WSPÓŁAUTORA

Mój udział w przygotowaniu publikacji pt. VO2 kinetics and tethered strength influence the 200-m front crawl stroke kinematics and speed in young male swimmers (Frontiers in Physiology, DOI: 10.3389/fphys.2022.1045178) obejmował:

- przeprowadzenie pomiarów,

- konsultacje przy przygotowaniu wstępnej wersji manuskryptu oraz zaakceptowanie jego ostatecznej wersji.

Oświadczam, że mój udział wkładu pracy w powstanie artykułu wyniósł 20%.

....

Podpis

Komisja Bioetyczna
przy Okręgowej Izbie Lekarskiej
w Krakowie

Lista obecności członków Komisji Bioetycznej
przy Okręgowej Izbie Lekarskiej w Krakowie
na posiedzeniu w dniu 5 czerwca 2020r.

dr Mariusz Janikowski ....
lekarz– specjalista chorób wewnętrznych,
diagnosta laboratoryjny
Zakład Diagnostyki Katedry Biochemii Klinicznej
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Komisja Bioetyczna
przy Okręgowej Izbie Lekarskiej
w Krakowie

Opinia

Nr 94/KBL/OIL/2020 z dnia 5 czerwca 2020 r.

Na posiedzeniu w dniu 5 czerwca 2020 r. Komisja zapoznała się z wnioskiem (dokumentacja w załączeniu) złożonym przez :

Koordynator Badania: mgr Kamil Sokołowski

Akademia Wychowania Fizycznego, Al. Jana Pawła II 78, 31-571 Kraków

Tytuł Protokołu: „ Czynniki morfologiczne, fizjologiczne oraz właściwości kinematyczne determinujące wyniki sportowe młodych pływaków w kraulu na piersiach".

Do wniosku dołączono:
Protokół badania
Streszczenie protokołu
Życiorys Głównego Badacza
Informacja dla Pacjenta
Formularz Świadomej Zgody Pacjenta
Formularz „Ochrony Danych Osobowych"
Polisa Ubezpieczenia Lekarza
Polisa Ubezpieczenia Ośrodka
Lista ośrodków biorących udział w badaniu

Komisja wyraża zgodę na przeprowadzenia badania na warunkach przedstawionych we wniosku.

Zgoda Komisji dla Ośrodka jest ważna do dnia ważności Polisy Ubezpieczeniowej
Skład i działanie Komisji zgodne z zasadami Dobrej Praktyki Klinicznej (GCP) oraz wymogami lokalnymi
Lista członków Komisji biorących udział w posiedzeniu stanowi załącznik do niniejszego dokumentu.
Pouczenie: W ciągu 14 dni od otrzymania niniejszej opinii Wnioskodawcy przysługuje prawo odwołania do Komisji Odwoławczej za pośrednictwem Komisji Bioetycznej przy OIL w Krakowie

Kraków, dnia 17.06.2020 r.

**Przewodniczący Komisji Bioetycznej
przy OIL w Krakowie**

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Article

Biological Age in Relation to Somatic, Physiological, and Swimming Kinematic Indices as Predictors of 100 m Front Crawl Performance in Young Female Swimmers

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Abstract: Background: Some swimmers reach high performance level at a relatively young age. The purpose of this study is to determine the relationship between adolescent female swimmers' 100 m front crawl race ($V_{total100}$) and several anthropometry, body composition, and physiological and specific strength indices. Methods: Nineteen adolescent female swimmers were examined for biological age (*BA*) and body composition. Oxygen uptake was measured during water-flume stage-test front crawl swimming with ventilatory thresholds examination. Specific strength indices were assessed during 30 s of tethered swimming. Stroke rate (*SR*), stroke length (*SL*), and stroke index (*SI*) were also examined. Results: *BA* was strongly correlated with anthropometrics and tethered swimming strength indices, and showed moderate to strong correlation with ventilatory thresholds. Speed of swimming in the race was moderately to largely correlated with speed at $\dot{V}O_2\ max - V_{\dot{V}O_2 max}$ (r = 0.47–0.55; $p < 0.05$)—ventilatory thresholds (V_{AT}, V_{RCP}) (r = 0.50–0.85; $p < 0.05$), *SL* (r = 0.58–0.62; $p < 0.05$), and *SI* (r = 0.79–0.81; $p < 0.01$). Conclusion: Results confirmed a significant role of biological maturation mediation on body composition and body size, ventilatory indices, and specific strength indices. *BA* was not a significant mediation factor influencing the swimming kinematics (*SL*, *SI*) and speeds of V_{AT}, V_{RCP} or $V_{\dot{V}O_2\ max}$, which were strong predictors of the 100 m race.

Keywords: female adolescents; biological maturation; swimming flume; ventilatory thresholds; front crawl swimming

1. Introduction

Female competitive swimming is a sport in which systematic training sessions and high training loads are implemented at an early age [1,2]. Training more and more extensively with gradually and periodically increasing intensity is undertaken along with the phenomenon of progressive biological maturation. The onset of puberty and mental, morphological, and physiological maturation interacts with the development of determinant factors, which affect swimming performance at the age-group level [3,4]. In considering competitive achievements, individual variations in intervals between earlier or later occurrences of growth spurts in one competitive age group cause variations in motor abilities as well as performance. Young swimmers at higher maturity levels are more likely to perform better than their less mature peers due to greater aerobic and anaerobic abilities [5–8]. Indeed, physical parameters such as body height, free fat mass or more athletic constitution, or bioenergetical indices such as swimming oxygen consumption have been shown in previous studies [2,9] to have an influence on the swimming performance of young women swimmers. Nevertheless, considering the swimming elite in the long term, Timakova and Klyuchnikova [9] pointed out that female swimmers with relatively slower maturation prevailed over the others, reaching high performance levels in adulthood. Monitoring growth as well as somatic and physiological traits in relation to biological maturation is therefore crucial to young athletes' training optimization and expectations of adequate sports performance [8]. Anthropometric measurements from earlier studies [10] revealed a strong relationship between morphological indices and swimming performance. Cochrane et al. [11] stated that morphological characteristics of young swimmers influence swimming performance and vary by events. Vorontsov et al. [7] claim that the strongest effect of maturity on physical conditioning and strength was indicated in the group of girls aged 13–14.

The number of studies of young swimmers in which oxygen uptake is measured directly in swimming is still very limited [12]. Malina et al. [13] noted that aerobic power of more mature female and male adolescent trained children was higher than in their less mature peers (differences ranging from 0.2 up to 1.0 $L \cdot min^{-1}$). Anaerobic metabolism is more developed in adults than in children, and it indicates that the maturation process influences the level of anaerobic energy production [4,14]. Tethered swimming is the most specific in-water test for strength measurement [15]. Nevertheless, according to Moran et al. [6], anaerobic power, peak force of arms, and free fat mass values are mediated by maturity, and swimmers who are already at peak high velocity are more likely to respond strongly to strength training.

When training age-group young women swimmers, technique should be the main concern, because it is one of the most important factors influencing present and future performance. Stroke length and stroke rate or stroke index are essential for an efficient swimming technique. Therefore, here the authors aim to analyze in adolescent female swimmers the influence of a set of morphological, specific strength, and physiological indices on the 100 m front crawl swimming race.

These studies are conducted while considering the impact (correlation or mediation effect) of biological age (*BA*) on swimming determinant factors: (a) body composition, (b) physiological and specific strength, and (c) kinematic indices of 100 m front crawl swimming. The subsequent aim of this study is to identify a set of variables which influence 100 m front crawl performance in female swimmers, but which are not directly related to *BA*.

The authors expect that *BA* will differentially influence the particular set of indices which could be higher for indicators related to body dimensions and strength, and lower for those related to specific swimming abilities: stroke kinematics and speed on metabolic thresholds (V_{AT}, V_{RCP}, $V_{\dot{V}O_2\ max}$).

2. Materials and Methods

2.1. Participants

Nineteen female swimmers (age 13.4 ± 0.26, min: 12.71, max: 13.73 years; height 1.66 ± 0.07 m; body mass 55.5 ± 9.3 kg) participated in this study. They were recruited from the most successful swimmers in their age category from the Cracow, Poland region. All of them were healthy and had licenses from the Polish Swimming Federation. All swimmers went through 4–5 years of systematic swimming, trained in at least 10 training units weekly and took part in national level competitions and national swimming championships for their age group. Despite swimming style specialization, all the participants performed in freestyle events regularly. The study was approved by the Regional Medical Chamber in Cracow on 5 June 2020 (No. 94/KBL/OIL/2020). All participants and their parents provided informed consent for their participation in intensive physical effort during this study (parents of all participants became acquainted with the study program and with a short description of the tests).

2.2. Body Composition and Biological Age

The body composition analyzer Tanita BC-418 (Tokyo, Japan) was used to assess segmental body composition. In addition to body mass (*BM*, kg) measurement, this device uses bioelectrical impedance analysis (BIA), a method of analyzing electrical responses to a weak electrical current introduced into the body. It is a research method that allows one to assess the human body composition with regard to extracellular and intracellular water, fat and lean mass, and cell mass, based on the differentiation of tissue resistance [16]. The body fat estimated by BIA has almost perfect reproducibility, making it an applicable research tool in studies that investigate body composition changes. FFM estimated by BIA correlates almost perfectly with reference methods, regardless of sex. Moreover, regarding quality, BIA has shown high reproducibility (correlation coefficient between 0.95 and 0.99 [17]. BIA is a reliable method of assessing the tissue composition of the body; its reliability and validity have been recognized in many independent studies: Jackson et al. [18]; Aandstad et al. [19]; Dave et al. [20]; Cortesi et al. [21]; Vasold et al. [22]. This method is successfully used by both untrained people and by athletes of all disciplines [23,24]. The participants dressed in underwear, stood with electrodes on their bare feet, and gripped handheld electrodes. This procedure provided data on fat free mass (*FFM*, kg), total body water (*TBW*, kg), and predicted muscle mass of body segments: arms ($m_{m\ arms}$, kg), trunk ($m_{m\ trunk}$, kg), and legs ($m_{m\ legs}$, kg). *FFM* and *TBW* values were also converted to percentages of *BM*. Biological age (*BA*) examinations of participants were conducted by an experienced anthropologist, who used the following calculation: $BA = (BH_{age} + BM_{age})/2$, where BH_{age} (height age) = age obtained from percentile charts (growth charts by The Children's Memorial Health Institute; 50th percentile was used to align height and mass with age) on the basis of the participant's body height and BM_{age} (mass age) = age obtained from percentile charts on the basis of the participant's body mass (growth charts by The Children's Memorial Health Institute, standardized and validated for the Polish population; 50th percentile was used to align height and mass with age). Additionally, pubertal development was assessed, by an experienced, formally trained anthropologist. Namely, Tanner stages based on pubic hair scale were estimated [25] and the date of menarche was obtained retrospectively (year, month, and, if possible, exact day). The recall method has previously been widely used in research, as well as justified as a reliable way to obtain the age of menarche [26,27]. It is a validated method, used for several dozen years all over the world [28,29]. It was also used many times in the youth population from Cracow [30].

Participants took part in two test trials. One contained tethered swimming, 100 m front crawl race and anthropometric measurements. During the second one, separated by 48 h, stage test in water flume was implemented. Before each test, the swimmers completed a 1000 m in-water warm up with low to moderate intensity.

2.3. Stage Test

The stage in a water flume (Figure 1) was conducted in a laboratory-controlled environment. All swimmers were informed about the testing procedure and performed a 1000 m in-water warm up, as before a competition. Participants wore a nose clip and were attached to a respiratory valve system with an expired air analyzer (Start 2000 MES, Poland). One minute of slow-paced swimming ensured their adjustment to the testing conditions. After an initial speed of 0.93 m s^{-1} providing moderate intensity of 30–40% $\dot{V}O_2max$, every two minutes a whistle signaled for them to increase speed by 0.06 m s^{-1}. Breath by breath, exhaled air was continuously sampled and saved (Ergo2000M software MES, Poland). $\dot{V}O_2max$, aerobic threshold (*AT*), and respiratory compensation point (*RCP*) were estimated [31]. The test was terminated after complete exhaustion and inability to maintain required swimming pace, reaching criteria of $\dot{V}O_2max$ examination [32]. Speed of the water flow and oxygen uptake (VO_2AT and V_{AT}, VO_2RCP and V_{RCP}, $\dot{V}O_2max$ and

$V_{\dot{V}O_2max}$) were assessed. In our study, all participants met the mentioned criteria, with RER (1.18 ± 0.17).

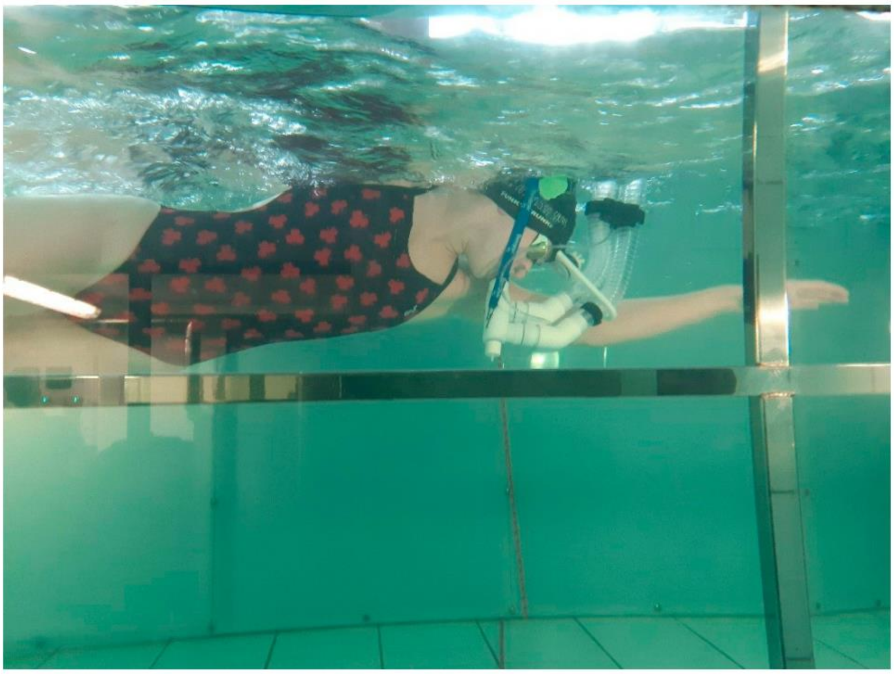

Figure 1. One of the swimmers going through a stage test procedure in a water flume.

2.4. Tethered Swimming Test

In the 30 s tethered swimming test, participants wore a waist belt and were connected to a steel pole (fixing point 0.49 m above the surface) by a 5.65 m steel cable and attached dynamometer (with 100 Hz recording frequency). The following indices were collected:

- Maximum value of force (F_{max}, N);
- Average value of force (F_{ave}, N);
- Force decline ($F_{decline}$, N), calculated from decrease in average force production in 0–10 and 20–30 s of the recording duration;
- Average impulse per single cycle (I_{ave}, N·s), defined as the integral of force over a period of time containing all full cycles divided by a number of completed cycles:

$$I_{ave} = \frac{\int_{t_0}^{t_1} Fdt}{n}$$

where: t_0 is the beginning of the first full cycle and t_1 is the ending of the last full cycle in the 30 s period.

2.5. Swimming Race

The 100 m race was carried out in a 25 m swimming pool that meets International Swimming Federation (FINA) requirements. The final results and split times of the trials were measured with an automatic timing device (Omega, Switzerland). Each one of the trial series was performed by three to four swimmers in order to imitate competition conditions. All trials were recorded with a (JVC GC-PX100BE, Japan) camera with 50 Hz framing. The camera was placed on a tripod at the bleachers, seven meters above the water surface on an extension in the middle point of the pool. The swimmers started from the blocks at the sound signal. Markers were placed at the side of the pool to indicate the line of 7 m from each of the walls and 10 m from the starting block. The pool was divided into three zones: (a) I turn zone (7 m), (b) surface swimming zone (11 m), and (c) II turn zone

(7 m). Including the first 10 m start zone, it resulted in a) 59 m for V_{STF} (start, turn, finish velocity) calculation and b) 41 m for $V_{surface}$ (surface swimming velocity) examination. Times for separate sectors were measured when swimmers' heads crossed the imaginary line linking markers at the sides of the pool (Kinovea ver. 0.8.15 software). The 100 m front crawl speed ($V_{total100}$) was calculated from the final time taken to complete the 100 m distance. The average *SR* (cycle min^{-1}) (ICC = 0.99, 95%, CI = 0.960–0.997) was calculated from 12 cycles (3 cycles from each of the 4 laps, measured in the surface swimming zone). *SL* was calculated from the 11 m surface swimming zones, during 4 laps. Stroke index *SI* (m^2·cycle s $^{-1}$) was calculated as: $SI = V_{surface} \cdot SL$.

2.6. Statistical Analysis

Individual, mean, and standard deviations (SD) computations for descriptive analysis were obtained for all studied variables. Measures of skewness, kurtosis and the Shapiro–Wilk test were used to assess the normality and homogeneity of the data.

One-way ANOVA with repeated measures and Tukey's HSD post hoc test were carried out to detect and present differences between: ($V_{total100}$, $V_{surface}$, V_{STF}). To identify the relationship between the variables, the Pearson correlations were computed between:

(a) Anthropometric, body composition indices and all the indices, tethered swimming test (F_{max} , F_{ave}, $F_{decline}$, I_{ave}) and swimming speed ($V_{total100}$, $V_{surface}$, V_{STF}),
(b) Stage test and swimming speeds or tethered swimming variables, and
(c) *SR*, *SL*, *SI* and $V_{total100}$, $V_{surface}$, V_{STF}.

To examine the possible mediation effect of *BA* on variables of V_{RCP}, $V_{\dot{V}O_2max}$, V_{AT}, *SI* and *SL*, which correlated the most with $V_{total100}$, were tested by mediation analysis with the Sobel test. Mediation analysis was made on the basis of three regression models [33]. The tests were conducted with STATISTICA 13.1 software (TIBCO Software Inc, Palo Alto, CA, USA). A significance level of $p \leq 0.05$ was established. Mediation analysis was prepared using R software ver. 4.5.0 with *mediation* package.

The magnitude of the correlations was determined using the modified scale by Hopkins (Hopkins, WG. Measures of reliability in sports medicine and science. Sports Med 30: 1–15, 2000.): trivial: r < 0.1; low: 0.1–0.3; moderate: 0.3–0.5; high: 0.5–0.7; very high: 0.7–0.9; nearly perfect > 0.9; and perfect: 1. To get significant results ($p < 0.05$) with sufficient power (80%) to detect at least a correlation coefficient of 0.6, the minimum required sample size for this study is 19. The formula for calculation is based on two-tailed test (Guenther, W C. 1977 Desk Calculation of Probabilities for the Distribution of the Sample Correlation Coefficient. The American Statistician).

3. Results

There was a significant difference between measured average speed values of: $V_{total100}$, $V_{surface}$, and V_{STF} (F = 127.0, $p \leq 0.001$). Post hoc Tukey's (HSD) test confirmed significant differences among all of the measured averages ($p \leq 0.001$). Figure 2 presents differences between all of the three analyzed averages.

Biological age (*BA*) presents high correlation relationship with body composition indices of *FFM* and *TBW* (r = −0.56, $p \leq 0.05$). The highest correlations (r = 0.88 to 0.92, $p \leq 0.001$) were found between biological age and *h*, *BM*, *FFM*, *TBW*, and $m_{m\ total}$ (Table 1).

The anthropometric indices of height, body mass, and muscle mass of particular body parts all showed significant moderate to very high relationship with tethered swimming indices. All tethered swimming indices correlated moderately to very highly with $m_{m\ total}$, $m_{m\ arms}$ (3.43 ± 0.54), $m_{m\ trunk}$ (24.03 ± 3.14), and $m_{m\ legs}$ (6.43 ± 0.93). *BA* was correlated at a very high level with maximal propulsion force and average impulse (Table 2).

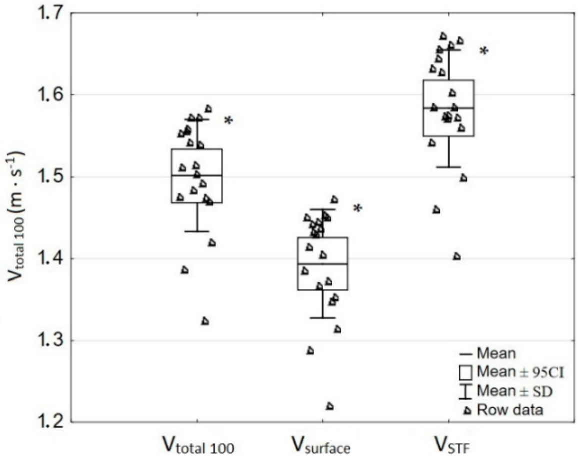

Figure 2. Comparison between average speed values of all of the distance ($V_{total100}$), surface swimming zones $\left(V_{surface}\right)$, and start, turn, and finish zones (V_{STF}) measured during 100 m crawl stroke race. * Significant difference from the other speeds; $p \leq 0.001$.

Table 1. Correlations between *BA* and anthropometric, body composition indices: *h*, *BM*, *FFM*, *FFM*, $m_{m\ total}$. In the top row, there are mean values and standard deviations (m ± SD) of anthropometric, body composition indices with corresponding ranges (min–max) presented. In the lower line there are values of Pearson correlations with corresponding *p* values.

Correlations	h (cm) 166.0 ± 6.60 Min: 153.0 Max: 174.0	*BM* (kg) 55.5 ± 9.30 Min: 39.3 Max: 73.4	FFM (kg) 42.46 ± 5.54 Min: 33.8 Max: 50.1	FFM (%) 76.94 ± 3.53 Min: 70.84 Max: 83.96	TBW (kg) 31.10 ± 4.24 Min: 24.2 Max: 38.1	TBW (%) 56.35 ± 2.65 Min: 51.91 Max: 61.58	$m_{m\ total}$ (kg) 40.3 ± 5.50 Min: 31.3 Max: 49.5
BA (years) 15.79 ± 2.38	0.89 $p < 0.001$	0.88 $p < 0.001$	0.92 $p < 0.001$	−0.56 $p = 0.012$	0.92 $p < 0.001$	−0.56 $p = 0.013$	0.92 $p < 0.001$

Table 2. Correlations of anthropometric, body composition indices: *BA*, *h*, *BM*, $m_{m\ total}$, $m_{m\ arms}$, $m_{m\ trunk}$, and $m_{m\ legs}$ with tethered swimming indices: F_{max}, F_{ave}, I_{ave}, and $F_{decline}$.

Correlations	BA (years)	h (cm)	*BM* (kg)	$m_{m\ total}$ (kg) 40.3 ± 5.50	$m_{m\ arms}$ (kg) 3.4 ± 0.54	$m_{m\ trunk}$ (kg) 24.0 ± 3.14	$m_{m\ legs}$ (kg) 6.4 ± 0.54
F_{max} (N)	0.78	0.78	0.63	0.66	0.64	0.68	0.61
227.64 ± 46.04	$p < 0.001$	$p < 0.001$	$p = 0.004$	$p = 0.002$	$p = 0.003$	$p = 0.001$	$p = 0.006$
F_{ave} (N)	0.76	0.65	0.70	0.74	0.77	0.77	0.68
79.7 ± 10.42	$p < 0.001$	$p = 0.003$	$p = 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p = 0.001$
I_{ave} (N·s)	0.78	0.71	0.70	0.75	0.74	0.77	0.68
50.6 ± 6.99	$p < 0.001$	$p = 0.001$	$p = 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p = 0.001$
$F_{decline}$ (N)	0.56	0.65	0.53	0.55	0.52	0.57	0.51
20.07 ± 8.33	$p = 0.013$	$p = 0.003$	$p = 0.020$	$p = 0.014$	$p = 0.022$	$p = 0.010$	$p = 0.026$

There was no significant correlation between body composition, tethered swimming indices, and free swimming speeds: $V_{total100}$, $V_{surface}$, V_{STF}.

The anthropometric, body composition indices correlated moderately to very highly with: $\dot{V}O_2AT$, $\dot{V}O_2RCP$, and $\dot{V}O_2max$ values. Significant correlations were observed between the tethered and stage tests F_{max} and ventilatory indices $\dot{V}O_2AT$ and $\dot{V}O_2RCP$ (r = 0.53 and r = 0.50, $p \leq 0.05$, respectively) (Table 3).

Table 3. Correlations of stage test physiological and kinematic indices: $\dot{V}O_2AT$, $\dot{V}O_2RCP$, and $\dot{V}O_2max$ with anthropometric, body composition indices.

Correlations	BA (Years)	h (cm)	BM (kg)	FFM (kg)	TBW (kg)	F_{max} (N)	F_{ave} (N)
$\dot{V}O_2AT$ (L·min^{-1}) 1.82 ± 0.09	0.52 $p = 0.024$	0.44 $p = 0.060$	0.63 $p = 0.004$	0.62 $p = 0.004$	0.62 $p = 0.004$	0.53 $p = 0.019$	0.42 $p = 0.070$
$\dot{V}O_2RCP$ (L·min^{-1}) 2.47 ± 0.45	0.66 $p = 0.002$	0.63 $p = 0.004$	0.57 $p = 0.011$	0.60 $p = 0.006$	0.60 $p = 0.006$	0.50 $p = 0.028$	0.37 $p = 0.121$
$\dot{V}O_2max$ (L·min^{-1}) 3.01 ± 0.42	0.45 $p = 0.051$	0.46 $p = 0.046$	0.39 $p = 0.095$	0.49 $p = 0.032$	0.49 $p = 0.032$	0.29 $p = 0.224$	0.29 $p = 0.221$

Significant correlations were observed between V_{AT}, V_{RCP}, $V_{\dot{V}O_2}$max and all swimming speeds: $V_{total100}$, $V_{surface}$, and V_{STF}. The level of ventilatory indices expressed in (L·min^{-1}) did not significantly correlate with swimming results. The best predictor of swimming results was V_{RCP} (Table 4).

Table 4. Correlations of stage test physiological and kinematics indices V_{AT}, VO_2AT, V_{RCP}, VO_2RCP, $V_{\dot{V}O_2\,max}$, and $\dot{V}O_2max$ with $V_{total100}$, $V_{surface}$, V_{STF}.

Correlations	V_{AT} (m·s^{-1}) 0.92 ± 0.09	$\dot{V}O_2AT$ (L·min^{-1})	V_{RCP} (m·s^{-1}) 1.15 ± 0.09	$\dot{V}O_2RCP$ (L·min^{-1})	$V_{\dot{V}O_2max}$ (m·s^{-1}) 1.23 ± 0.06	$\dot{V}O_2max$ (L·min^{-1})
$V_{total100}$ ($\frac{m}{s}$) 1.50 ± 0.07	0.53 $p = 0.020$	−0.10 $p = 0.690$	0.81 $p < 0.001$	0.23 $p = 0.336$	0.47 $p = 0.044$	0.27 $p = 0.264$
$V_{surface}$ ($\frac{m}{s}$) 1.39 ± 0.07	0.50 $p = 0.031$	−0.13 $p = 0.597$	0.85 $p < 0.001$	0.22 $p = 0.357$	0.55 $p = 0.014$	0.29 $p = 0.226$
V_{STF} ($\frac{m}{s}$) 1.58 ± 0.07	0.54 $p = 0.018$	−0.07 $p = 0.778$	0.76 $p < 0.001$	0.23 $p = 0.334$	0.39 $p = 0.104$	0.24 $p = 0.315$

High to very high correlations were observed between *SL* and *SI* with $V_{total100}$, but *SR* did not correlate with this speed (Table 5). The kinematic indices were not correlated with body height.

Table 5. Correlations of kinematic indices of *SR*, *SL*, and *SI* with: $V_{total100}$, $V_{surface}$, V_{STF}.

Correlations	SR (cycle·min^{-1}) 47.31 ± 3.24	SL (m) 1.77 ± 0.15	SI ($\frac{m^2}{s}$) 2.48 ± 0.29
$V_{total100}$	−0.05 $p = 0.844$	0.61 $p < 0.001$	0.81 $p < 0.001$
$V_{surface}$	0.02 $p = 0.935$	0.58 $p = 0.010$	0.79 $p < 0.001$
V_{STF}	−0.10 $p = 0.681$	0.62 $p = 0.005$	0.79 $p < 0.001$

For *BA* mediation analysis we selected variables (V_{AT}, V_{RCP}, $V_{\dot{V}O_2max}$, *SL*, and *SI*) which were significant predictors of the swimming race in this study ($V_{total100}$). This was carried out to examine the effect of maturation (*BA*), which could influence the relation of selected predictors on swimming performance.

None of the tested variables—V_{RCP}, $V_{\dot{V}O_2max}$, V_{AT}, *SI*, or *SL*—were identified as mediated by biological age. The mediation analysis showed moderate or strong correlations between variables and $V_{total100}$ (Figure 3a–e).

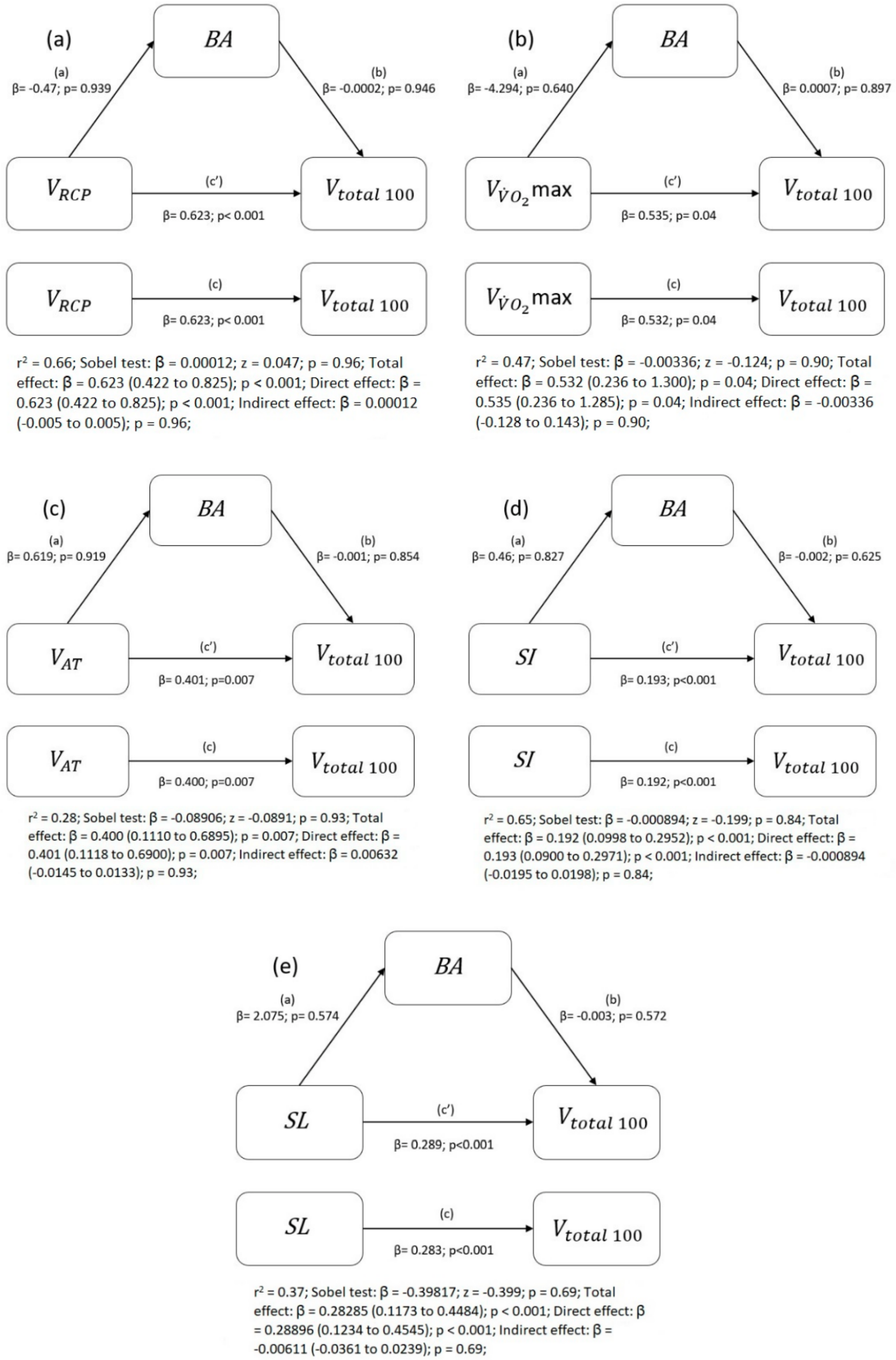

Figure 3. Mediation models illustrating the level of mediation effects of the relation between the independent variables of: (**a**) V_{RCP}, (**b**) $V_{\dot{V}O_2max}$, (**c**) V_{AT}, (**d**) *SI*, (**e**) *SL* and dependent variable of $V_{total100}$. β and corresponding *p*-values are presented. β of total (c), direct (c′), and indirect (a,b) effects are presented with 95% confidence intervals, *p*-value.

4. Discussion

This study showed that 100 m front crawl race results of adolescent female swimmers were significantly related to swimming endurance: V_{AT}, V_{RCP}, $V_{\dot{V}O_2}$ max and stroke kinematics *SL* and *SI*. The main finding is that those particular relationships were observed without significant mediation effect of *BA*. As far as we know, $V_{\dot{V}O_2}$ max was not presented when evaluating adolescent female swimming performance. In this study, $V_{\dot{V}O_2}$ max showed a significant relationship (r = 0.47, $p \leq 0.05$) with the 100 m front crawl race, but also our choice of V_{AT} and , V_{RCP} as predictors of swimming performance is rare in young swimmers.

In young swimmers, even in short race distances with duration over one minute, aerobic power development is crucial [1]. Malina et al. [13] noted that aerobic power of swimmers more advanced in maturation was higher than in their less mature peers. In longitudinal studies of the development of cardiorespiratory capacity, which have rarely been conducted with young swimmers, there has been observed an ability to perform increased volume and intensity of training load [8]. Those changes linked with growth and development of aerobic power translate into an increase in swimmers′ achievements [1]. $\dot{V}O_2\ max$ (L·min^{-1}) results presented in our study show no significant correlation (r = 0.19, $p \leq 0.05$) with 100 m race results, as in the Unnithan et al. [34] study of female adolescent swimmers (age 15.3 ± 1.5 years). Lack of significant correlations between $\dot{V}O_2\ max$ and performance in our study might be caused by not fully utilized cardiovascular and respiratory range and by use of anaerobic energy source in the 100 m race. The noted results also significantly show higher speeds of V_{AT} and V_{RCP} in relation to the 100 m race, which must be the advantages of better developed swimming economy and endurance of the best swimmers. In our study, the results for absolute maximal oxygen uptake (3.01 ± 0.42 L·min^{-1}) were higher than in the study of Plyley, Wells and Schneiderman-Walker [35] (2.7 ± 0.3 L·min^{-1}) assessed during tethered swimming. The reasons for that could be that females in our group, despite similar chronological age, were taller with greater body mass and reached greater exhaustion in the flume stage test (higher values of *RER*). The V_{RCP} relationship with the 100 m front crawl race presented in our study shows a similar strength as that of critical velocity of 30 min aerobic endurance test of young females (age 11.5 ± 0.6 years) and swimming performance in their personal best events (r = 0.55) [36]. We found that a 100 m front crawl race of young female swimmers is highly correlated with an ability to maintain higher swimming intensity and endurance—V_{RCP}.

In this study, anaerobic tethered swimming indices were not significantly related to 100 m race but remained influenced by *BA*. Taylor S, MacLaren D, Stratton G [5] observed a substantial increase in mean force production in tethered swimming in 13-year-old swimmers, which is explained by the development of the glycolytic energy system caused by maturation. Geladas, Nassis, and Pavlicevic [37] have not found a significant relationship (r = −0.18, $p \leq 0.05$) between grip strength and a 100 m race of young female swimmers (age 12.68 ± 0.06 years), but in male participants this correlation was strong (r = −0.73; $p \leq 0.01$). In a study of Silva et al. [38], tethered swimming indices F_{max} and F_{ave} were not significant predictors of young female swimmers' sprint performance. A study of Oliveira et al. [39] revealed the significance of controlling for the maturation effect of specific strength evaluation in adolescent swimmers, showing biological maturation mediated positively between anthropometric or body composition and the propulsive force of arms. As mentioned by Vorontsov [8], early maturers demonstrate greater physical abilities and performance level than their peers who are normal or late maturers. According to Moran et al. [6], swimmers who have already reached the peak height velocity are more likely to respond more to strength training. In our study, anthropometrics showed no significant relationship with the 100 m race, so we can state the advantage of better efficiency of swimming technique (*SI, SL*) of leaders instead of strength. However, undoubtedly, also in female swimming the appropriate level of strength must be reached. This study did not find in female swimmers significant influence of height on the 100 m race, *SL*, or *SI*, but

Lätt et al. [2] observed significant correlation (r = 0.41, $p \leq 0.05$) between *SL* and height of adolescent swimmers. Silva et al. [40] showed longer *SL* and higher height in age 11–12 female swimmers, affected by advanced calendar age and technique development of earlier maturers. Geladas et al. [37] also did not find any relationship between anthropometrics and the 100 m race in 13-year-old female swimmers, but they revealed body height, hand length, and horizontal jump association with *BA*, which explained only 17% of the variance of the 100 m race. Zuozienė and Drevinskaitė [41] reported in young female swimmers (11.8 ± 0.4) a lack of significant correlation between anthropometrics and the 200 m race. They concluded that, in girls versus boys, anthropometrics predicts swimming performance less. On the other hand, physical characteristics of young swimmers might influence swimming performance [2,11]. Toussaint and Beek [42] pointed out that young swimmers' ability to increase maximal swimming velocity is associated with better force-generating capacity caused by age-related growth in muscle size. Vorontsov et al. [7] concluded that the strongest effect of maturity on physical development and strength could be observed in girls aged 13–14.

The relationship between stroke kinematics and the 100 m race showed that *SI* and *SL* are good swimming speed predictors, especially here for young females, because they are free of *BA* mediation. This indicates that their size depends mostly on the type of technique dedicated to swimming training. Mezzaroba and Machado [43] pointed out that *SR*, *SL*, and *SI* included in multiple linear regression of swimmers aged 10–17 could explain almost 100% (R^2 = 0.99) of 100 m race results of young swimmers. Jürimäe et al. [4] stated that *SI* may be an important indicator of swimming economy in adolescent swimmers. Morais et al. [44] revealed a strong relation between adolescent girls' (12.31 ± 1.09 years) 100 m race time result and *SI* (r = −0.82, $p \leq 0.01$) and *SL* (r = −0.61, $p \leq 0.05$), which is very similar to our speed performance and kinematics (r = 0.81, $p \leq 0.01$ and r = 0.61, $p \leq 0.01$, respectively). Lätt et al. [12] also presented high partial correlation between time of 100 m front crawl performance in young male swimmers (age 15.2 ± 1.9 years) and *SI* (r = −0.643; $p \leq 0.05$).

Despite objective strengths of the presented study, some limitations should also be noted. For example, the method used to assess biological age is not validated, or the small sample of participants examined may limit the application of the conclusions in regards to the wide swimming community.

5. Conclusions

This study analyzed significant predictors of the 100 m front crawl race in adolescent female swimmers: front crawl swimming endurance (V_{AT}, V_{RCP}, $V_{\dot{V}O_2}max$) and stroke kinematics (*SL*, *SI*). The noted predictors were not mediated by *BA*. These results showed that young female swimmers rely on trained physiological capacity and efficient front crawl stroke technique and less on somatic traits or strength. The identified predictors are certainly susceptible to the influence of well-thought-out, planned swimming training.

Key Points

- Biological age must be taken into consideration when evaluating young female swimmers' abilities in regards to training and performance;
- Efficiency of sprint swimming technique reflected by *SL* and *SI*, crucial in young female swimmers may be more dependent on the training used and less dependent on biological age;
- Swimming speed at ventilatory thresholds and maximal oxygen uptake is valuable in terms of assessment of the physiological build-up in relation to performance in adolescent female sprint swimming.

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Study of talented young male swimmers – scientific approach to the kinematic and physiological predictors of 400-m front crawl race

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Purpose: The purpose of this study was to assess the influence of physiological and kinematic predictors on 400-m front crawl race in young male swimmers and to consider the interrelation between them. *Methods*: Nineteen male swimmers took part in this study (age: 13.5 ± 0.44 years, height: 168.6 ± 7.77 cm, body mass: 56.9 ± 10.57 kg). Measurements of physiological parameters were conducted using expired air analyzer (Start 2000 MES, Poland) during step-test in water flume. Kinematic indices were computed while analyzing video recording of 400-m front crawl race. To check for possible influence of biological age (*BA*) diversity in studied group, partial correlation with age control was computed. *Results*: Swimming to exhaustion in water flume defined as speed at maximum oxygen uptake and anaerobic threshold ($V_{\dot{V}O_2 \max}$ and V_{AT}) occurred to be strongly positively correlated with 400-m race speed. Speed in surface swimming zones (V_{surface}) was related to ability of kinematics adjustment and significantly correlated with stroke index (*SI*). V_{surface} at the beginning and the end of the race, i.e., at 1st, 7th and 8th lap interplayed with stroke rate (*SR*) measured at corresponding laps. *Conclusions*: Our study showed that 400-m front crawl performance of young male swimmers is strongly dependent on swimming efficiency developed with aerobic conditioning. Significant role of proper pacing strategy was also identified, which indicates that race pace training should be implemented.

Key words: *adolescent swimming, front crawl, ventilatory thresholds, maximum oxygen uptake, kinematic indices, pacing strategy*

1. Introduction

Swimming performance of young swimmers is determined by the interaction of morphological, physiological, biomechanical and psychological factors, based on individual genetic endowment and continuously modulated by the training process [17], [29], [35]. Narrowing down, best performance in swimming depends on the amount of metabolic energy spent in transporting the body mass of the athlete and on the economy of aquatic locomotion over the unit of swimming distance [44]. Difference of swimming economy from one adolescent swimmer to another, also depending on competitive skill – swimming kinematics, physiological capacity or morphological development [12], [18], [36]. Metabolic energy related to physiological development of young athlete is influenced by growth and maturation, it was observed at both aerobic [24] and anaerobic [6] conditioning level. Appropriate level of aerobic conditioning of the talented young swimmer is a matter of great importance when our goal is to lead him to compete in the close and further future [31].

At the elite level, the best mid- and long-distance swimmers are expected to demonstrate high aerobic capacity with high enough anaerobic threshold, and competition usable aerobic power – $\dot{V}O_{2\max}$. Therefore, the level of these indicators, if possible, is periodically monitored during the training of age groups in order to further gradually improve endurance [20],

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[39] and it is combined with proper technique skills development.

Interesting, however, is the relationship between morphological development and swimming performance kinematics – stroke rate (*SR*), stroke length (*SL*), stroke index (*SI*) including (or excluding) the influence of maturation state of young swimmers [1]. So far, measurements (free swimming) of oxygen consumption have been rarely carried out to assess the aerobic conditioning of young swimmers [22], [41], [43] but researchers have interest in this topic [3]. Indeed these valuable assessments of aerobic preparation, need to be performed during exercise that fully utilizes the aerobic metabolism. Interestingly, these tests include different procedures when swimming at least the 400 meters or during longer gradual speed increases [9], [31], [38]. The blood lactate or oxygen uptake outcome of all-out 400-m front crawl swimming could illustrate level of aerobic conditioning and aerobic maximal velocity [10]. Fernandes et al. [14] performed incremental test with the time limit at $\dot{V}O_{2\max}$ examination – time of maintaining swimming speed corresponding to maximal oxygen uptake – showing that it is possible that the maintaining of slow component of $\dot{V}O_{2\max}$ is very similar to 400-m front crawl race duration. In young swimmers however, it's complicated by the level of maturation which affect the aerobic conditioning, performance by enhancing those more advanced in puberty [24], [32].

In swimming, the aerobic condition is shaped during water training, along with the kinematic characteristics of locomotion related to both anthropometry and the persistence to technique building up [18], [22], [26]. Douda et al. [13] claim that when considering young swimmers performance there is no consensus about which determinants are the most important, but growth process (maturation) should be always considered. Morais et al. [28], after analyzing large number of literature, stated that in young swimmers talent identification could be characterized as multifactorial, holistic. Abbott et al. [2] indicate technique and anthropometric variables which in their opinion have the biggest influence on youth swimmers performance.

Morais et al. [29] stated that biomechanics is responsible for 60% of the young swimmers performance. Silva et al. [37] showed that, in age-group swimmers, technique training is crucial and the level of technique efficiency is influenced by maturation process. There are three the most frequently used indices which characterize swimming technique: stroke rate (*SR*), stroke length (*SL*) and stroke index (*SI*). The *SI* is considered as the one which explains the most a level of swimming efficiency [23], [27] but less experienced (especially they) young swimmers and also the others have often difficulties with saving energy, and/or consciously manipulating the *SR* and *SL* as fatigue inevitably increases with the race distance covered.

Taking the dependencies that result in the development of talented swimmers into account, we set ourselves the goal of examining: (a) physiological, biomechanical determinants of front crawl performance collected in aquatic motorized swimming flume during stage test and 400-m race, (b) the interplay between physiological and kinematic indices with swimmers maturity and 400-m freestyle race, (c) changes in kinematic indices through the 400-m freestyle race.

It is expected that kinematic and physiological indices associated with higher aerobic endurance (higher anaerobic thresholds), will be significant predictors of 400-m front crawl performance simultaneously with the ability to use appropriate kinematics along with the fatigue.

2. Materials and methods

2.1. Participants

Nineteen male swimmers (age 13.5 ± 0.44 years) participated in this study. They were recruited as the most talented swimmers from their age category from Kraków region, Poland. Participants presented swimming level which resulted in mean value of 352 FINA points for 400-m front crawl race. All of them were healthy and had licenses from the Polish Swimming Federation. Participants height (168.6 ± 7.77 cm, stadiometer – Sieber Hegner Maschinen AG, Switzerland) and body mass (56.9 ± 10.57 kg, Tanita BC-418, Japan) were measured and body mass index calculated (19.6 ± 2.28 kg/m^2). The study was approved by the Regional Medical Chamber in Kraków on 5 June 2020 (No. 94/KBL/OIL/2020). All participants and their parents provided informed consent for their participation in intensive physical effort during this study (parents of all participants became acquainted with the study program and with a short description of the tests).

2.2. Biological age

Biological age (*BA*) examination of participants was conducted by experienced anthropologist and was calculated as follows: BA = [(BHage + BMage)/2], where: BHage – age obtained from percentile charts on the basis of the participant's body height, Bmage – age obtained from percentile charts on the basis of the participant's body mass. Additionally, pubertal development was assessed. Tanner stages based on pubic hair scale were estimated [8].

2.3. Physiological indices measurements

Stage test in water flume (Fig. 1) in laboratory--controlled environment (temperature, humidity) was conducted. Sufficiently in advance, swimmers were asked to rest the day before the test and to maintain their daily diet. Before entering the water flume swimmers were instructed to testing procedure and went through 1000 meters in-water warm-up, as before the competition. Entering the test procedure swimmers fitted nose clip and were attached to respiratory/valve system with expired air analyzer (Start 2000 MES, Poland). Than placed own body in order to marker on the bottom of the flume (with eyesight controlling the position of the body relative to the marker through entire test) and to adjust proper valve system (attached to a rod-alike construction, just above a swimmers' head). One minute slow pace swim ensured to adjust to testing conditions. Whistle signal started (from –0.93 m/s), 2-minutes of 0.06 m/s speed increased steps. Breath by breath exhaled air was continuously sampled by expired air analyzer and saved for further analysis (Ergo2000M software MES, Poland). $\dot{V}O_{2\max}$, Aerobic Threshold (AT), Respiratory Compensation Point (RCP) were estimated according to Beaver et al. [5]. The test was terminated after complete exhaustion and inability to maintain required swimming pace reaching criteria of $\dot{V}O_{2\max}$ examination [19]. Time of test termination (t_{test}), speed of the water flow (V_{AT}, V_{RCP}, $V_{\dot{V}O_{2\max}}$) and oxygen uptake (VO_2AT, VO_2RCP, $\dot{V}O_{2\max}$) accompanying to occurring the ventilatory indices or were also assessed. Swimmers were also filmed through entire test duration (JVC GC-PX100BE, Japan) in order to calculate the kinematic indices of: SR, SL, SI at V_{AT}, V_{RCP}, $V_{\dot{V}O_{2\max}}$. Mentioned indices were calculated from 3 cycles at each step.

2.4. 400-m front crawl race

400-meter all-out test was carried out in a 25-m swimming pool that meets International Swimming Federation (FINA) requirements. Final results and split times of the race were measured with automatic timing device (Omega, Switzerland). Each one of the race series were performed by five to four swimmers, similarly, as in competition conditions. Participants reached 105.2% of their personal best time in 400-m front crawl while performing in our study. All trials were recorded with (JVC GC-PX100BE, Japan) camera with 50 Hz framing. Camera was placed at the tripod at the tribune, 6 metres above the water surface in the extension of the middle point of the pool. Starting from the block swimmers were asked to emerge until the 10th meter. To separate the areas of surface swimming, the pool was divided into zones. Markers were placed at the side of the pool to locate the line of 7 metres from each of the walls. For the first lap one marker was attached 10 metres from the starting block. Pool (excluding first lap) was divided to three zones: I – turn zone (7 m), II – surface swimming zone (11 m), III – turn zone (7 m). Including first 10 m start zone it resulted in: a) 227 meters for V_{STF} (start, turn,

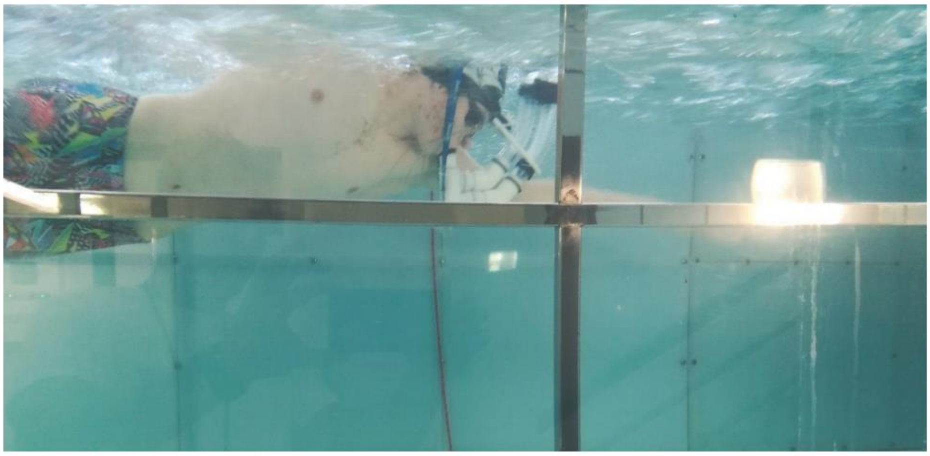


Fig. 1. Swimmer during stage test procedure in water flume

finish velocity) calculation, b) 173 meters for V_{surface} (surface swimming velocity) examination. Times for separate sectors were measured when swimmers head cross the imaginary line linking markers at the sides of the pool using program Kinovea – ver. 0.8.15. Stroke kinematic indices *SR*, *SL*, *SI* were calculated from surface swimming zones. The *SR* (cycle · min^{-1}) from each of surface swimming zones (extracted from 3 cycles). The *SL* (m) was estimated as: $\text{SL} = \frac{V_{\text{surface}}}{SR}$. Stroke index *SI* (m^2 · cycle · s^{-1}) was calculated as: $SI = V_{\text{total}} \cdot SL$. Kinematic results were averaged for every 50-m lap. Intraclass correlation (ICC) for *SR* calculation process was: ICC = 0.99, 95%CI = 0.990 – 0.999.

2.5. Statistical analysis

Standard statistical methods were used to calculate means and standard deviations (mean ± SD). The normality of the data assumptions were examined with the Shapiro–Wilks test. One-way ANOVA with repeated measures and Tukey HSD post-hoc test was carried out to detect and present differences between average velocities (V_{total}, V_{surface}, V_{STF}). Examination for relationship were computed between: a) stage test indices of: V_{AT}, V_{RCP}, $V_{\dot{V}O_{2\max}}$, $\dot{V}O_{2AT}$, $\dot{V}O_{2RCP}$, $\dot{V}O_{2\max}$, b) kinematic indices (*SR*, *SL*, *SI*) of 400-m race or stage test and: (i) *BA* using Pearson's correlations; and (ii) V_{total} or V_{surface} using partial correlations controlled with *BA* factor. Partial correlations with *BA* control were also executed to show a relationship between V_{surface} and *SR*, *SL*, *SI* on the each lap of 400-m race and at last between kinematic indices of stage test *SR*, *SL*, *SI* and physiological indices of $\dot{V}O_{2AT}$, $\dot{V}O_{2RCP}$, $\dot{V}O_{2\max}$.

Sphericity assumption of the data entered in one-way ANOVA repeated measures (V_{surface}, V_{turn}, V_{total}, *SR*, *SL*, *SI)* was examined with Mauchly's test. Assumption of sphericity was not met, than MANOVA Wilk's Lambda test was conducted to assess differences between the laps means of kinematic variables. Square or cubic trends were adjusted for the values of kinematic variables measured for each lap of 400-m front crawl race. The tests were conducted with STATISTICA 13.1 software (StatSoft, Inc). Significance level of $p \leq 0.05$ were established.

3. Results

A significant differences are shown between separated speeds of 400-m front crawl race: V_{total},

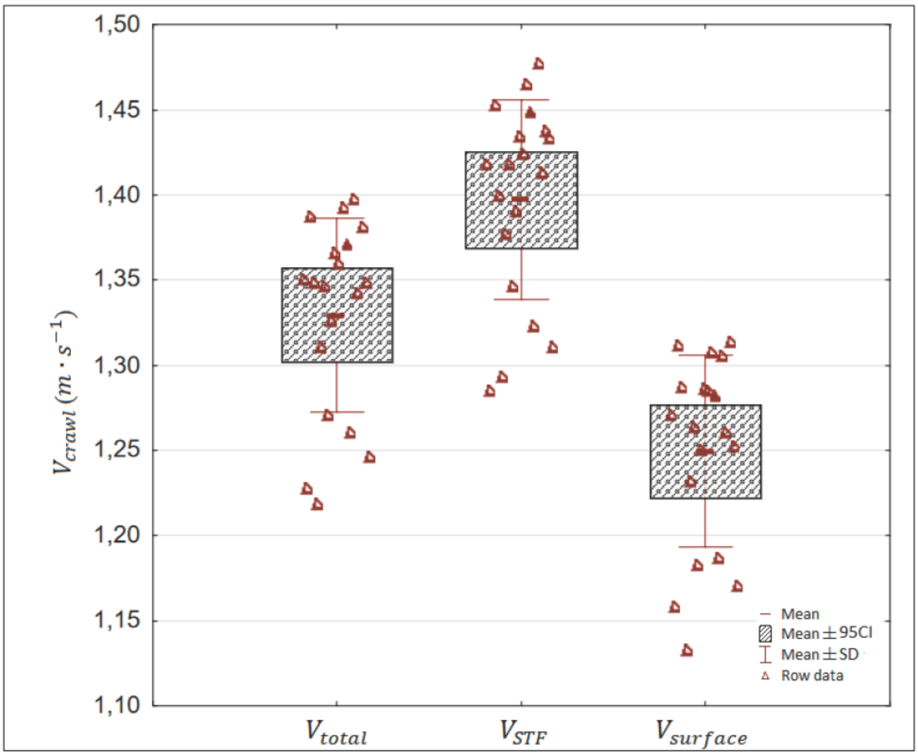


Fig. 2. Comparison between average speed values of: all of the distance (V_{total}), surface swimming zones (V_{surface}) and start, turn and finish zones (V_{STF}) measured during 400-m front crawl race

$V_{surface}$, V_{STF} ($F = 100.1$; $p < 0.001$). Post-hoc Tukey's (HSD) test confirmed significant differences among all of the measured averages ($p < 0.001$). In Figure 1, differences between analysed speeds are presented.

No significant but positive correlations were noted between biological age (*BA*) and V_{AT}, V_{RCP}, $V_{\dot{V}O_{2max}}$. Significant partial correlations controlled for *BA* were found between VAT, $V_{\dot{V}O_{2max}}$ and V_{total} (Table 1).

Table 1. Pearson correlations between *BA* and: V_{AT}, V_{RCP}, $V_{\dot{V}O_{2max}}$ (A). Partial correlations controlled with *BA* between *stage test* kinematics indices: V_{AT}, V_{RCP}, $V_{\dot{V}O_{2max}}$ and result of 400-m front crawl race (V_{total}) (B)

	Correlations	V_{AT} [m·s^{-1}] 0.89 ± 0.11	V_{RCP} [m·s^{-1}] 1.17 ± 0.06	$V_{\dot{V}O_{2max}}$ [m·s^{-1}] 1.24 ± 0.06
A	*BA* [years] 14.74 ± 1.82	0.01	0.26	0.12
B	V_{total} [m·s^{-1}] 1.33 ± 0.06	0.48 *	0.28	0.68 **

* Significant relationship between analysed indices with $p \le 0.05$; ** $p \le 0.01$.

There were strong, significant relationships between *BA* and $\dot{V}O_{2AT}$, $\dot{V}O_{2RCP}$, $\dot{V}O_{2max}$. With *BA* control V_{total} did not significantly interplay with $\dot{V}O_{2AT}$, $\dot{V}O_{2RCP}$, $\dot{V}O_{2max}$, although partial correlation between $\dot{V}O_{2AT}$ and V_{total} was close to significant (Table 2).

Table 2. Pearson correlations between *BA* and: $\dot{V}O_{2AT}$, $\dot{V}O_{2RCP}$, $\dot{V}O_{2max}$ (A). Partial correlations controlled for *BA* between *stage test* physiological indices: $\dot{V}O_{2AT}$, $\dot{V}O_{2RCP}$, $\dot{V}O_{2max}$ and result of 400-m front crawl race (V_{total}) (B)

	Correlations	$\dot{V}O_{2AT}$ [*l*·min^{-1}] 2.06 ± 0.46	$\dot{V}O_{2RCP}$ [*l*·min^{-1}] 2.85 ± 0.58	$\dot{V}O_{2max}$ [*l*·min^{-1}] 3.46 ± 0.71
A	*BA* [years]	0.63 **	0.71 **	0.57 *
B	V_{total} [m·s^{-1}]	0.43 $p = 0.07$	0.05	0.33

* Significant relationship between analysed indices with $p \le 0.05$; ** $p \le 0.01$.

Strong and significant correlations were found between *BA* and *SL*, *SI*. The kinematic indices of *SR* and *SL* showed no relationship with $V_{surface}$ when controlled for *BA*, but *SI* significantly interplayed with $V_{surface}$ (Table 3).

Table 3. Pearson correlations between *BA* and: *SR*, *SL*, *SI* (A). Partial correlations, controlled for *BA* between kinematic indices: *SR*, *SL*, *SI* of 400-m front crawl race and $V_{surface}$ (B)

	Correlations	*SR* [cycle·min^{-1}] 37.6 ± 3.62	*SL* [m] 2.01 ± 0.19	*SI* $\left[\frac{m^2}{s}\right]$ 2.51 ± 0.30
A	*BA* [years]	–0.44 $p = 0.06$	0.54 *	0.53*
B	$V_{surface}$ [m·s^{-1}] 1.25 ± 0.06	0.28	0.24	0.62**

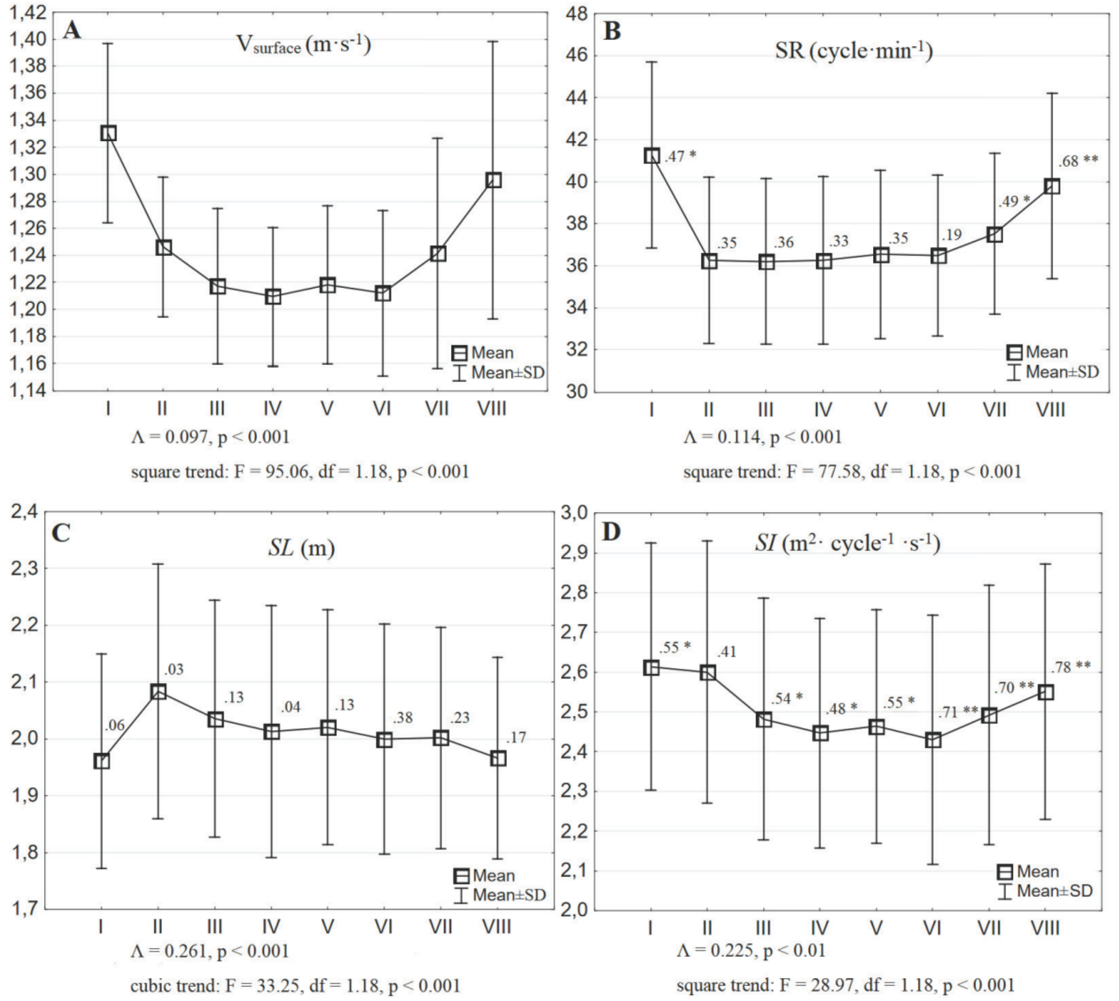
* Significant relationship between analysed indices with $p \le 0.05$; ** $p \le 0.01$.

In further proceedings, we decided to present the changes in kinematic variables and their interdependence to $V_{surface}$ also excluding the impact of biological age (these results are inserted close to squares of values averages in the graphs – Figs. 3B–D). We noted significant and high interrelation of *SR* and $V_{surface}$ on the first, seventh and the last lap (Fig. 3B), and also on the most laps between *SI* and $V_{surface}$ (Fig. 3D).

There were significant differences between 50-m laps speed ($V_{surface}$) in 400-m front crawl race ($\Lambda = 0.097$, $p < 0.001$) (Fig. 3A), stroke rate (*SR*) for each of 50-m ($\Lambda = 0.114$, $p < 0.001$) (Fig. 3B), stroke length (*SL*) ($\Lambda = 0.261$, $p < 0.001$) and stroke index (*SI*) ($\Lambda = 0.225$, $p < 0.001$). For $V_{surface}$, *SR*, *SI* curves square trend was established as the most suitable one (Figs. 3A, B, D). Cubic trend was established as the best fitted to *SL* curve (Fig. 3C).

For each of 50-m lap of average swimming velocity (V_{total}) ($\Lambda = 0.035$, $p < 0.001$) and velocity in turn zones (V_{turn} ($\Lambda = 0.157$, $p < 0.001$) significant differences were measured (Figs. 4A, B). Square trend was established as the most suitable one for V_{total} curve and cubic trend for V_{turn} curve.

Additionally, we decided to compute Pearson's correlation of stage test *SR*, *SL*, *SI* calculated at ventilatory thresholds and $\dot{V}O_{2max}$ with $V_{surface}$. We found that *SI* at *AT* was significantly correlated with $V_{surface}$ ($r = 0.48$, $p < 0.05$), when excluding *BA* in partial correlations it was nonsignificant.



* Significant relationship between analysed indices with $p \leq 0.05$; ** $p \leq 0.01$.

Fig. 3. $V_{surface}$ (A), *SR* (B), *SL* (C) and *SI* (D) indices on each 50-m lap of 400-m front crawl race. Wilk's test results (Λ) and trend's established for the curves (square trend, cubic trend). Partial correlations controlled for *BA* between $V_{surface}$ and *SR*, *SL*, *SI* at particular laps are presented in graphs B, C, D

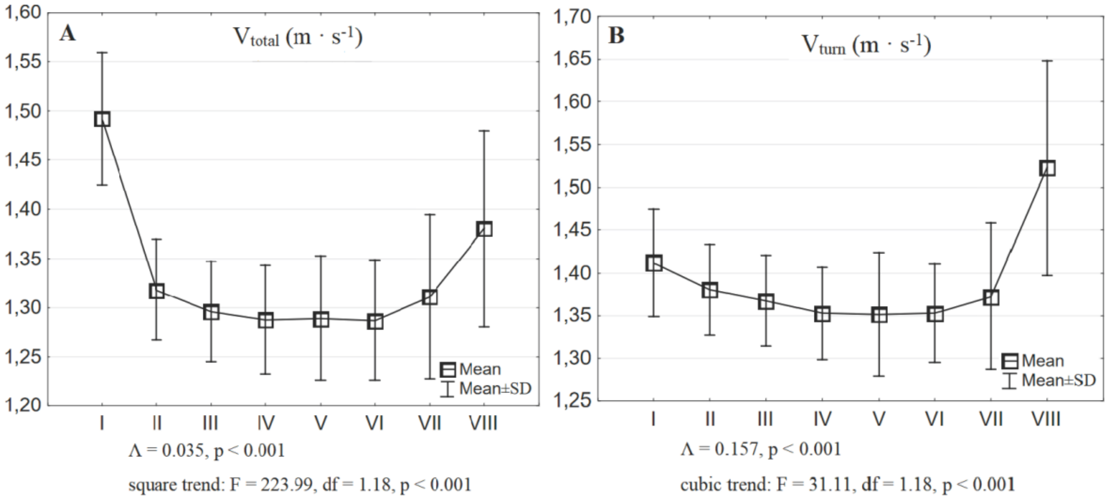


Fig. 4. V_{total} (A) and V_{turn} (B) values on each 50 m lap of 400-m front crawl race. Wilk's test values (Λ) and trend's established for the curves (square trend, cubic trend)

4. Discussion

These results show the rarely observed influence of physiological preparation and simultaneous kinematic-technical shaping on swimming results of young puberty male swimmers. In the presented study the result of 400-m front crawl race (V_{total}) was positively, significantly interrelated with physiological swimming efficiency – $V_{\dot{V}O_{2max}}$ ($r = 0.68$, $p < 0.01$) and with V_{AT} ($r = 0.48$, $p < 0.05$). Furthermore, the $V_{surface}$ interplayed strongly with 400-m *SI* kinematic ($r = 0.62$, $p < 0.01$) and was also significantly correlated to stage test – *SI* at *AT* ($r = 0.48$, $p < 0.05$). These studies also show the magnitude of the influence of maturation on the level of physiological and kinematic indicators. Thus, the physiological indices of oxygen uptake at metabolic thresholds – $\dot{V}O_{2AT}$, $\dot{V}O_{2RCP}$, $\dot{V}O_{2max}$ did not interplayed significantly with results of 400-m front crawl race, when controlled for *BA*. On the other hand, interplay between $\dot{V}O_{2AT}$ and V_{total} (close to significant) shows the importance of a well-developed aerobic energy generation system in 400-m swimming, which was at the same time strongly dependent on *BA* (Table 2). Similarly, *BA* influenced on the shaping of kinematics, but their level and impact on $V_{surface}$ we can state had to be mainly dependent by training (Table 3).

Considering these results, we can ask whether high oxygen uptake at the time of the appearance of subsequent metabolic thresholds is beneficial? Does higher oxygen uptake values at thresholds mean lower economy? It is possible to state that, the level of aerobic capacity represented by $\dot{V}O_{2max}$ seems to influence the efficiency of aerobic system, but also enhance the anaerobic mechanisms of energy production used in 400-m front crawl race. Thus, higher $\dot{V}O_{2max}$, supports the fast creatine phosphate reconstruction and the elimination of lactate [31]. These positive effect of high aerobic capacity level combined with the ability to swim fast using as much of oxidative energy as possible, could lead to later fatigue occurrence in 400-m front crawl race. Fernandes and Vilas-Boas [15] reported that best high level swimmers with great level of aerobic power are less likely to maintain the $V_{\dot{V}O_{2max}}$ max for the longer time than the other talented swimmers who possess even higher aerobic capacity. The power of the former lies in the ability to use the entire oxygen potential supported-supplemented by a well-trained glycolytic component [33]. It could be also like that between different level or in more proficient swimmers with higher aerobic power but having smaller aerobic capacity the work will be not able to continue at the highest intensities [9].

Study of Jürimäe et al. [18] revealed that, among young male swimmers, *SL, SI* and VO_{2peak} presented the strongest correlations with 400-m front-crawl results. Zacca et al. [42] reported that technique (*SR*, *SI*) showed the greatest influence on 400-m front crawl performance of age-group swimmers among others physiological, anthropometrical indices. Similarly to Abbott et al. [2] we found significant interrelation between *SI* and maturation level. In the study by Strzała et al. [40], the 400-m front-crawl performance was highly correlated with *SR*, propulsive phases of arm index of coordination (IdC) total body length and anerobic threshold assessed in arm-cranking. In the study by Mezzaroba and Machado [27], multiple linear-regression including only 1 variable of *SI* explained 89% of 400-m front crawl performance in young male swimmers. Similarly, in the study by Lätt et al. [23] stepwise regression analysis showed that *SI* was the best predictor of 400-m front crawl performance ($R^2 = 0.449$; $p < 0.05$) distinguished from the equation contained physiological, biomechanical parameters. It is similar to this study, where *SI* controlled for *BA* occurred to be strongly correlated ($r = 0.62$, $p < 0.01$) with $V_{surface}$. Our results also correspond to the other premises of care for shaping the appropriate kinematics of limb movements [16], [30].

In this study *SI*, reached at *AT* was significantly interrelated to $V_{surface}$. It could be explained by the fact that more efficient swimmers reached their *AT* later with respectively higher oxygen consumption, it means that their energetics was more supported by oxidative mechanisms. It means that swimming economy must be basically more dependent on the efficient oxidative mechanisms, always when the swimming distance is going to be longer. A valuable outcome of the presented study was that $V_{surface}$ at first, 7th and 8th lap was significantly correlated with *SR* measured. It seems that ability to increase *SR* at the very end of the race is crucial for maintaining speed and to compensate drop of *SL*. It was shown by Mezzaroba and Machado [27], who stated that the not fully developed anaerobic mechanisms of adolescent swimmers could not provide enough energy for maintaining the proper coordination patterns (mainly increase *SR*) at maximum speeds at longer races. It is in accordance with the study of Dekerle et al. [11], where it has been shown that muscle fatigue leads to progressive increase in the energy cost in swimming and fall of kinematic parameters (also index of coordination highly related to *SR*). Zacca et al. [43] concluded that decrease in 400-m front crawl velocity after 4 weeks training cessation is caused by significantly lower *SR*. They stated that identification of $V_{\dot{V}O_{2\max}}$ is more applicable for evaluating energetics in age-group swimmers than $\dot{V}O_{2\max}$ or energy cost of swimming – C [kJ · m^{-1}]. It is because that in their study $V_{\dot{V}O_{2\max}}$ values were related to the individual 400-m front crawl performance. Our results are consistent with these observations because V_{surface} and $V_{\dot{V}O_{2\max}}$ in this study are almost identical. We could state that $V_{\dot{V}O_{2\max}}$ sets up the limit for the 400-m front crawl performance.

It was observed in our study that V_{surface}, V_{total}, *SR* and *SI* values change in a parabolic pattern and were parallel to each other (Figs. 3A, B, D, Fig. 4A), square trend suited for them the best. This pacing strategy was noted earlier by Robertson et al. [34]. It means that first lap of the race is the fastest, the middle ones are the slowest and the last one is close to the fastest ones from the beginning of the race, it is known also as fast-start-even strategy. The results presented in Fig. 4A are a good example of parabolic pacing strategy implication. Study by Mauger et al. [25] revealed that elite 400-m front crawl swimmers choose fast-start-even and parabolic pacing strategy most often. They claimed that these strategies are chosen because of their high effectiveness in terms of work-rate distribution. Bishop et al. [7] provided the physiological explanation for the fast-start-even pacing advantage, and showing the need of initial high intensity. It requires the use of phosphocreatine reserve resulting in a further greater oxidative contribution, which prevents swimmers from higher muscle fatigue level due to great anaerobic energy involvement and also saves the anaerobic pathway for the finish of the race.

Changes observed in our study in speed and *SL*, *SR* along 400-m front crawl race were similar to those presented by Laffite et al. [21]. They also noted drop of *SR* at the beginning of the second lap which ends at the final laps with the significant increase of *SR* and the progressive decrease of *SL* all along the distance. They also underline that *SL* decrease during all-out 400-m front crawl race seems not to be responsible for performance level, but the only way to sustain a high swimming velocity is increase of *SR*. It is in accordance with results of Aujouannet et al. [4], they found a relation between drop in swimming velocity in the middle-distance front crawl swimming and decrease of *SR* values.

5. Conclusions

The present study demonstrates result of significant interrelation between 400-m front crawl race (V_{total}) with physiological and kinematic swimming efficiency indices of young male swimmers. It was shown that swimming speeds and oxygen uptake at ventilatory thresholds has a great importance for swimmers' performance level and their swimming efficiency. We could also observe how maximal oxygen uptake and oxygen uptake at ventilatory thresholds as well as kinematic indices *SR*, *SL*, *SI* are strongly influenced by biological maturation. It gives a premise (information) for the implementation of sustainable training momently and in the long term.

This results can indicate that level of oxygen uptake influences the ability to maintain efficient stroke kinematic pattern, represented by the higher *SI* of young male swimmers. It could be explained by later fatigue occurrence and saving up anaerobic energy supplies for the last part of the race. Most of the swimmers used fast-start-even or parabolic strategy where *SL* decreased along covered laps and *SR* presented the U-shaped, square trend. Ability to increase *SR* at the final laps of the race in this study was crucial in 400-m front crawl race in young male puberty swimmers.

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Body composition and anthropometrics of young male swimmers in relation to the tethered swimming and kinematics of 100-m front crawl race.

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Body composition, anthropometrics of young male swimmers in relation to the tethered swimming and kinematics of 100-m front crawl race.

Background: The aim was to analyse the relationship of body mass and predicted muscle mass of body segments on swimming kinematics and tethered swimming indices, and further assess the influence of those indices on 100-m front crawl performance of adolescent male swimmers. **Methods:** In 19 volunteer swimmers (age: 13.5 ± 0.44 years, height: 168.6 ± 7.77 cm, body mass: 56.9 ± 10.57 kg), the predicted muscle mass of body segments was assessed with bioelectrical impedance analysis. The kinematic indices of swimming (stroke rate - *SR*, stroke length - *SL*, and stroke index - *SI*) were calculated from a video recording of a 100-m front crawl race. The strength indices (maximum and average value of force, average impulse per single cycle, force decline) were collected in a 30-second front crawl tethered swimming test. **Results:** The average tethered swimming force was positively correlated with surface swimming speed (0.505; $p \leq 0.05$). Indices of *SL*, *SI* were influenced by average impulse per single cycle (0.58, 0.55; $p \leq 0.05$), and further the *SI* was strongly correlated with most specified speed indices of the 100-m race (0.59; $p \leq 0.05$). **Conclusions:** It can be stated that the ability of force development in a single stroke, owing to strong interrelation with *SI*, is a good predictor in talent identification among young swimmers.

Key words: sprint swimming, age-group swimmers, tethered swimming, kinematic indices

BACKGROUND

Swimming performance at the elite level consists of a composition of such factors as technique (stroke technique, coordination), physical conditioning (strength, flexibility, aerobic and anaerobic conditioning), and psychological profile.[1] Each significant swimming community developing the training process for younger participants cares about their proper sustainable development[2] The benefit of training at an early age should be provided to all trainees.[3] to provide the most talented individuals with a chance for long-term development.[4,5] One of the main goals of swimming research is to identify and evaluate the variables that predict swimming results in the near and distant future. Obtaining information, on the one hand, focuses on the features explaining the current sports results of juniors[2]; on the other hand, it should provide premises for the prognosis of long-term development towards elite adulthood.[6]

Results of young swimmers are strongly related to such anthropometric characteristics as body height (BH)[7,8] muscle mass [9] and better technique but it has been considered as multifactor, holistic issue[10] Swimmers defined as asthenic, ectomorphic somatotype and at slower maturation pace are less likely to their performance being influenced by BH, it is because of lack of muscular component and lower capacity to generate energy.[11] Prediction of adult BH is crucial in terms of planning swimmers sports development and anticipating their senior performance. Although there is no simple rule in elite swimming that the longer the body is, the faster the swimming[12], a sufficient BH must be met.[13] A similar assumption applies to muscle mass. Nevertheless, there are reasons to search for the most promising young, pubertal swimmers when those taller, heavier, possessing greater arm span and hand length reach greater velocities in 50-m front crawl swimming.[14] Similar morphological features determined the performance at 100 m of adolescent male swimmers.[15], while Lätt et al.[16] additionally noted that the weight and density of the skeleton in better performers was higher. In young swimmers, the acceleration of biological development, as well as BH and muscle mass increase are closely related to the development of strength and anaerobic and aerobic energy sources[4,5] and, in consequence, the ability to generate propulsion force.

It has been proven that a greater force generated in tethered[17] or semi-tethered[18] swimming is positively correlated with better performance in young talented individuals. A tethered swimming test has been successfully used as a reliable estimator of adolescent swimmers' sprint performance.[19,20] It is also known that data collected during tethered swimming is exposed to biases due to hips immobilization, different velocity of the swimmer relative to water[21]-In young adolescent swimmers it is unknown how differences in biological age (BA) influences relationship between strength abilities, anthropometrics and swimming velocity. Many different protocols of tethered have been used to assess force generated by swimmer in water[22,23] and it is still used as a valuable test evaluating anaerobic performance.[24]

Shaping basic endurance, strength, and speed in swimming, it is important to increase swimming efficiency, manifested by basic kinematic indicators: stroke index (SI), stroke length (SL), and stroke rate (SR).[15,16,25,26] Optimal proportions of SL and SR values provide greatest mechanical efficiency expressed by higher SI value but growth process could significantly influence mentioned stroke parameters.[27] SI is one of the best predictors explaining the performance of adolescent swimmers in short.[7,16,28], as well as in middle or long swimming races.[29,30] It could be due to *SI* is a product of *SL* and swimming velocity (*V*). De Mello Vitor & Silveira Böhme[7] also demonstrated that *SI* and *SL*, among multiple indices, were significant predictors of 100-m front crawl performance, which was supported by a study by Morais et al.[31] Silva et al.[32] revealed that *SL* and *SR* correlated significantly with 50-m front crawl swimming speed in adolescent boys. Barbosa et al.[33] identified *SR* as one of the determining indices of young swimmers 200-m front crawl performance. Maintaining or increasing the SR values during the race is crucial to compensate the decrease in SL caused by fatigue.[34]

The authors' aim was to analyse the relationship of morphological traits, especially the predicted muscle mass, and swimming kinematics and tethered swimming performance in adolescent male swimmers. The authors assume that indicators related to the force generated in tethered swimming may be significant in predicting the results of 100-m front crawl performance of adolescent swimmers at different maturation level. A potential impact of differences in biological maturation among the participants will be excluded by assessing their biological age (*BA*) and its control in the statistical analysis.

METHODS

Participants

The study involved 19 male swimmers (age: 13.5 ± 0.44, min.: 12.89, max.: 14.78 years). They were recruited as swimmers with the highest performance level in their age category from the Cracow region, Poland. The participants presented a swimming level which resulted in a mean value of 354.18 ± 49.74 International Swimming Federation (FINA) points for a 100-m front crawl race. All of them were healthy and had licences from the Polish Swimming Federation. All the swimmers had a 4–5-year experience in systematic swimming, performed at least 10 training sessions weekly, and took part in national level competitions and national swimming championships for their age group (Trained/Developmental level in classification of McKay et al.[35]). Despite the swimming style specialisation, all the individuals participated in freestyle events regularly. Their BH (mean ± standard deviation: 168.6 ± 7.77 cm; anthropometer: Sieber Hegner Maschinen AG, Switzerland, accuracy of 1 mm) and body mass (BM) (56.9 ± 10.57 kg; Tanita BC-418, Japan, accuracy of 0.01 kg) were measured and body mass index was calculated in accordance with the following formula: body weight [kg]/body height [m]2 (19.6 ± 2.28). The research was approved by the Bioethics Committee at the Regional Medical Chamber (No. 94/KBL/OIL/2020). All subjects and their parents provided informed consent for their participation in intensive physical effort during this study (parents of all participants became acquainted with the study program and a short description of the tests).

Body composition and biological age

The body composition analyser Tanita BC-418 (Tokyo, Japan) was used to assess segmental body composition. In addition to *BM* (kg) measurement, the device performs bioelectrical impedance analysis, a method of analysing tissue composition on the basis of varying electrical responses to the weak electrical current introduced into the body. Bioelectrical impedance analysis is a reliable method of assessing the tissue composition of the body; its reliability and validity has been recognised in many independent studies.[36–38] The participants, dressed in underwear, stood on the electrodes with their bare feet and gripped the handheld electrodes. This procedure provided data on the predicted muscle mass of body segments: arms ($m_{\text{m arms}}$, kg), trunk ($m_{\text{m trunk}}$, kg), and legs ($m_{\text{m legs}}$, kg). *BA* examinations (*BA*: 14.74 ± 1.82 years) were conducted by an experienced anthropologist, who used the following calculation: $BA = (BH_{\text{age}} + BM_{\text{age}}) / 2$, where BH_{age} was the age obtained from percentile charts (growth charts by The Children's Memorial Health Institute; 50$^{\text{th}}$ percentile was used to align *BH* with age) on the basis of the participant's *BH*, and BM_{age} was the age obtained from percentile charts (growth charts by The Children's Memorial Health Institute, standardised and validated for the Polish population; 50th percentile was used to align *BM* with age) on the basis of the participant's *BM.* Additionally, pubertal development was assessed by an experienced, formally trained anthropologist. Namely, Tanner stages based on pubic hair scale were estimated. [39]

The participants took part in two maximum efforts. One involved tethered swimming (first), the other was a 100-m front crawl race (second). Before each test, the swimmers completed a 1000-m in-water warm-up with low to moderate intensity. After tethered swimming test participants performed at least 15 min warm-down after and had additional 30 min for passive recovery.

Tethered swimming

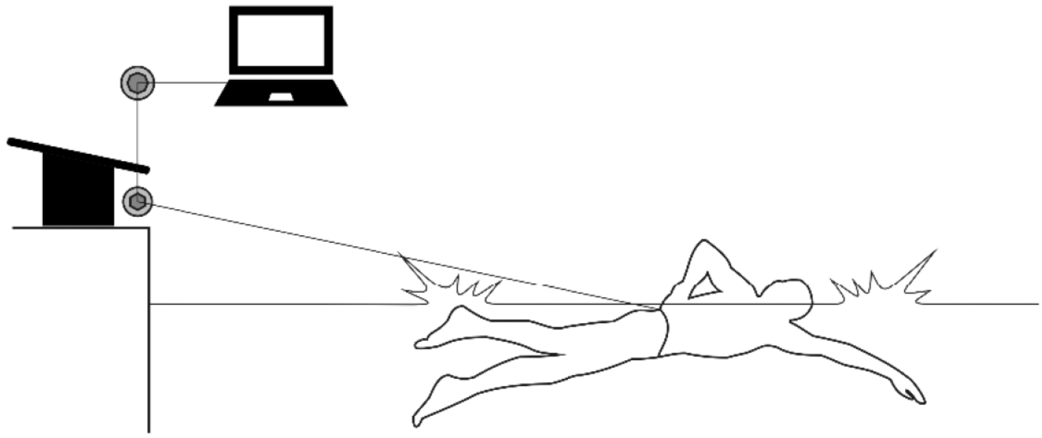

Figure 1. Illustration of the apparatus used to perform the 30-second tethered swimming test.[40]

In the 30-second tethered swimming test, the participants wore a waist belt and were connected to a steel pole (fixing point: 0.49 m above the surface) by a 5.65-m steel cable and an attached dynamometer (recording frequency: 100 Hz) (Figure 1). Before the test participants got at least 20 s to familiarize with the new conditions and try perform some movements at low intensity. The following indices were collected:

- maximum value of force (F_{max}, N);
- average value of force (F_{ave}, N);
- force decline (F_{decline}, N), calculated from a decrease in average force production in 0–10 and 20–30 seconds of the recording duration;

- average impulse per single cycle (I_{ave}, N · s), defined as the integral of force over a period of time containing all full cycles divided by a number of completed cycles:

$$I_{\text{ave}} = \frac{\int_{t_0}^{t_1} F dt}{n},$$

where: t_0 is the beginning of the first full cycle and t_1 is the end of the last full cycle in the 30-second period.

100-m front crawl race

The 100-m race was carried out in a 25-m swimming pool that met the FINA requirements. The ultimate results and split times of the race were measured with an automatic timing device (Omega, Switzerland, accuracy of 0.01 s). Each of the race series was performed by five to four swimmers, similarly to competition conditions. All trials were recorded with a camera (JVC GC-PX100BE, Japan, framing of 50 Hz). The camera was placed on a tripod at the stands, 6 m above the water surface, in the extension of the middle point of the pool. Starting from the block, the swimmers were asked to emerge before reaching the 10^{th} meter. To separate the areas of surface swimming, the pool was divided into zones. Markers were placed at the side of the pool to locate the line of 7 m from each of the walls. For the first lap, the first marker was attached 10 m from the starting block, the second one at 15 m, and the third 7 m from the wall. The pool (excluding the first lap) was divided to three zones: I – turn zone (7 m), II – surface swimming zone (11 m), III – turn zone (7 m). Including the first 10-m start zone, this resulted in: (a) 59 m for the start, turn, finish velocity (V_{STF}) calculation, (b) 41 m for surface swimming velocity (V_{surface}) examination. Times for separate sectors were measured when the swimmer's head crossed the imaginary line linking the markers at the sides of the pool; the Kinovea version 0.8.15 software was used. Stroke kinematic indices of *SR*, *SL*, *SI* were calculated from surface swimming zones. The average *SR* (cycle · min^{-1}) (intraclass correlation coefficient: 0.96, 95% confidence interval: 0.841–0.989) was determined from 12 cycles (3 cycles form each of the 4 laps, measured in the surface swimming zone). *SL* (m) was estimated as: $SL = \frac{V_{\text{surface}}}{SR}$; *SI* ($\text{m}^2$ · cycle · s^{-1}) was calculated as: $SI = V_{\text{total}} \cdot SL$.

Statistical analysis

Individual, mean, and standard deviation computations for descriptive analysis were obtained for all studied variables. Measures of skewness and kurtosis, as well as the Shapiro-Wilk test were used to assess the normality and homogeneity of the data.

One-way analysis of variance with repeated measures and Tukey's honestly significant difference (HSD) post-hoc test were carried out to detect and present differences between: V_{15}, V_{total100}, V_{STF}, V_{surface}. To identify the relationship between the variables, partial correlations controlled for the *BA* factor were computed between: (a) tethered swimming test indices (F_{max}, F_{ave}, F_{decline}, I_{ave}) and anthropometric characteristics (*BM*, *BH*, $m_{m\ arms}$, $m_{m\ trunk}$, $m_{m\ legs}$); (b) tethered swimming test indices and 100-m front crawl race results, including front crawl kinematics (*SR*, *SL*, *SI*); (c) *SR*, *SL*, *SI* and V_{15}, $V_{total100}$, $V_{surface}$, V_{STF}.

The magnitude of the correlations was determined by using the modified scale by Hopkins[41]: trivial: r < 0.1; low: 0.1–0.3; moderate: 0.3– 0.5; high: 0.5–0.7; very high: 0.7–0.9; nearly perfect > 0.9; and perfect: 1.

RESULTS

There were differences between the measured speeds of the 100-m front crawl race: $V_{total100}$, V_{STF}, $V_{surface}$, V_{15} ($F = 209.80$; $p < 0.001$) (Figure 2). Post-hoc Tukey's HSD test indicated the significant differences among all of the measured averages ($p < 0.001$).

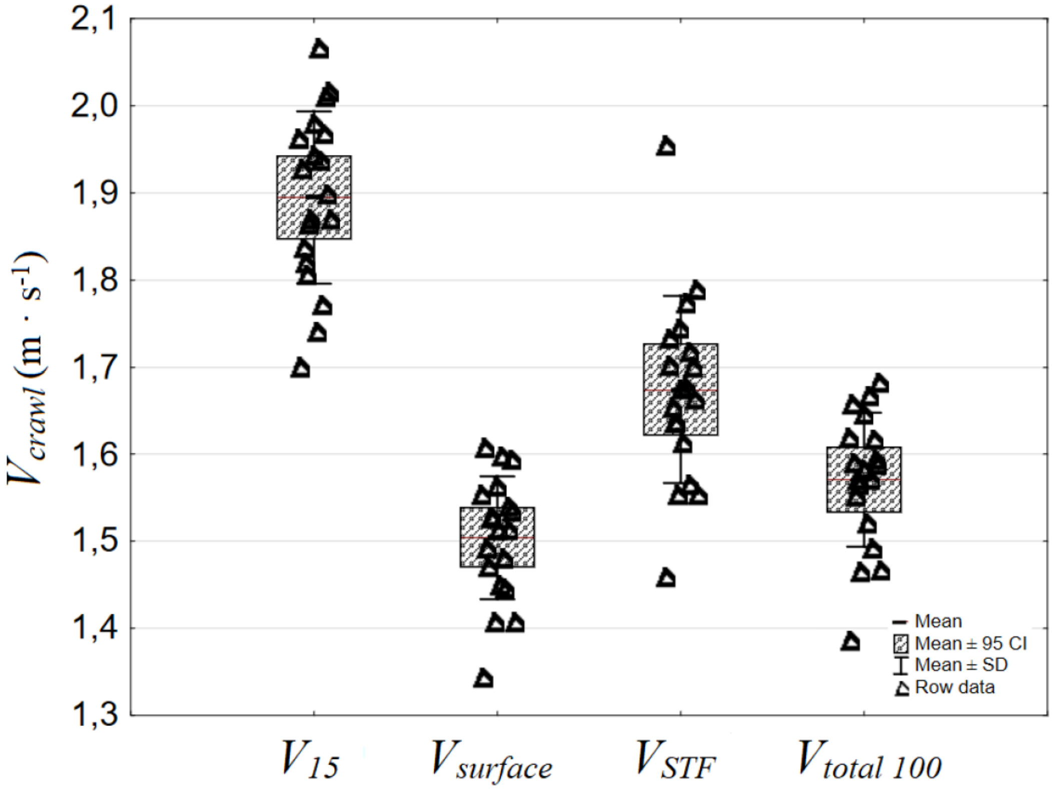

Figure 2. Comparison of the average speed values for the first 15 m (V_{15}), all of the distance ($V_{total100}$), surface swimming zones ($V_{surface}$), and start, turn, and finish zones (V_{STF}) measured during the 100-m crawl stroke race

A positive linear relationship was observed between F_{max} and $m_{m\ arms}$. F_{ave} and I_{ave} correlated significantly with $m_{m\ trunk}$ and $m_{m\ legs}$. *BM* was moderately associated with F_{ave}. The relationship between $F_{decline}$ and $m_{m\ legs}$ was close to significant (Table 1).

Table 1. Partial correlations controlled for *BA* between F_{max}, F_{ave}, $F_{decline}$, I_{ave} and *BH*, *BM*, $m_{m\ arms}$, $m_{m\ trunk}$, $m_{m\ legs}$.

Correlations	F_{max} (N) 260.73 ± 55.81	F_{ave} (N) 86.93 ± 16.98	$F_{decline}$ (N) 10.96 ± 4.06	I_{ave} (N · s) 54.22 ± 12.89
BH (cm)	0.226	0.105	0.031	0.028
BM (kg)	0.221	0.483*	0.275	0.424
$m_{m\ arms}$ (kg) 4.56 ± 0.90	0.341*	0.397	0.336	0.434
$m_{m\ trunk}$ (kg) 25.03 ± 3.77	0.364	0.554*	0.322	0.512*
$m_{m\ legs}$ (kg) 8.05 ± 1.51	0.344	0.543*	0.437 p = *0.069*	0.499*

*p ≤ 0.05; **p ≤ 0.01

F_{ave} exhibited a significant relationship with indices of swimming speed: $V_{total100}$, V_{STF}, $V_{surface}$, and its relationship with V_{15} was close to significant. There were no correlations between F_{max}, I_{ave} , $F_{decline}$ and indices of swimming speed (Table 2).

Table 2. Partial correlations controlled for *BA* between F_{max}, F_{ave}, $F_{decline}$, I_{ave} and V_{15}, $V_{total100}$, V_{STF}, $V_{surface}$.

Correlations	F_{max} (N)	F_{ave} (N)	$F_{decline}$ (N)	I_{ave} (N · s)
V_{15} (m·s^{-1}) 1.89 ± 0.10	0.343	0.458 p = *0.056*	0.122	0.382
$V_{total100}$ (m·s^{-1}) 1.57 ± 0.08	0.148 p = 0.559	0.469*	0.242	0.110
V_{STF} (m·s^{-1}) 1.68 ± 0.11	p = 0.498	0.536*	0.249	0.113
$V_{surface}$ (m·s^{-1}) 1.50 ± 0.07	p = 0.424	0.505*	0.256	0.143

*p ≤ 0.05; **p ≤ 0.01

Figure 3. Values of kinematic indices of $V_{surface}$ for each 25-m lap of 100-m front crawl race and values of correlations with F_{ave} controlled for *BA*.

Among the tethered indices, only I_{ave} was significantly moderately correlated with *SL* and *SI*. The relationship between I_{ave} and *SR* was close to significant (Table 3).

Table 3. Partial correlations controlled for *BA* between F_{max}, F_{ave}, $F_{decline}$, I_{ave} and *SR*, *SL*, *SI*.

Correlations	F_{max} **(N)**	F_{ave} **(N)**	$F_{decline}$ **(N)**	I_{ave} **(N · s)**
SR (cycle·min^{-1}) 47.75 ± 4.49	0.079 p = 0.756	0.157 p = 0.534	0.291 p = 0.241	-0.428
SL (m) 1.84 ± 0.19	0.033 p = 0.896	0.132 p = 0.600	–0.210 p = 0.359	0.575*
SI ($\frac{m^2}{s}$) 2.77 ± 0.36	0.148 p = 0.557	0.377 p = 0.123	–0.068 p = 0.789	0.549*

*p ≤ 0.05; **p ≤ 0.01

SI correlated significantly with V_{15}, $V_{total100}$, and $V_{surface}$. There was no association of *SR* and *SL* with swimming speed indices (Table 4).

Table 4. Partial correlations controlled for *BA* between indices of swimming speed and *SR*, *SL*, *SI*

Correlations	***SR* (cycle·min^{-1})**	***SL* (m)**	***SI* ($\frac{m^2}{s}$)**
V_{15} (m·s^{-1})	–0.056	0.395	0.662**
$V_{total100}$ (m·s^{-1})	0.354	0.121	0.571*
V_{STF} (m·s^{-1})	0.405	–0.051	0.370
$V_{surface}$ (m·s^{-1})	0.388	0.129	0.593**

*p ≤ 0.05; **p ≤ 0.01

SR value from 4th lap was negatively, low correlated with I_{ave}. *SL* from 1th, 2th and 4th laps was positively, moderately correlated with I_{ave}. There was significant, moderate relationship between I_{ave} and *SI* from 1th and 2th laps. F_{ave} was significantly correlated with $V_{surface}$ from 1th and 2th laps (Figure 3).

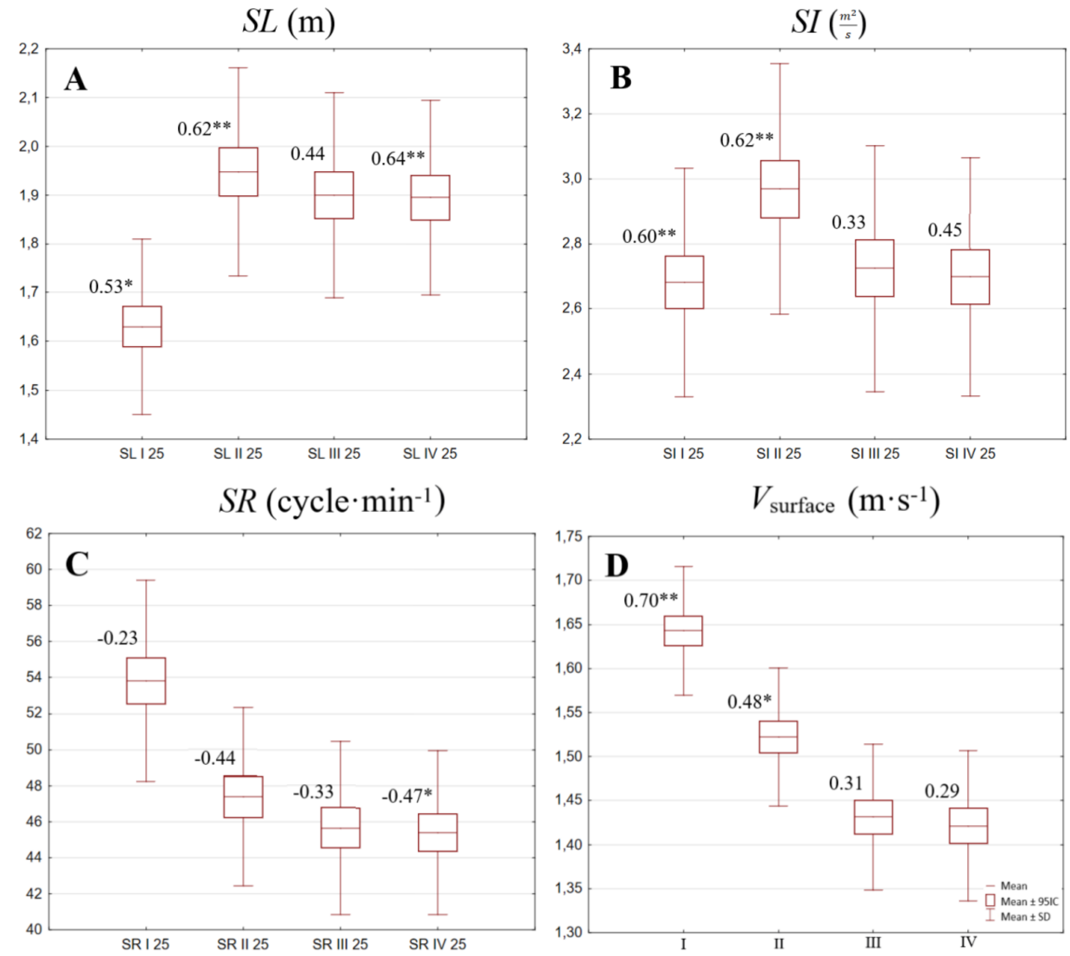

Figure 3. Values of kinematic indices of: *SL* (A), *SI* (B) and *SR* (C) for each 25-m lap of 100-m front crawl race and values of correlations with I_{ave} controlled for *BA*. Values of V_{surface} (D) of each lap of 100-m front crawl race and values of correlations with F_{ave}.

Discussion and practical implications

The data presented in our study revealed a significant relationship between indices of swimming speed and the tethered swimming F_{ave} (Table 2). It was also observed that the level of propulsion force was determined by the indices of body composition: *BM*, $m_{\text{m arms}}$, $m_{\text{m trunk}}$, $m_{\text{m legs}}$ (Table 1). The interrelation between kinematic variables of *SL*, *SI*, and I_{ave} was a valuable observation (Table 3). Indices of swimming speed were highly correlated with *SI* (Table 4).

The anthropometric characteristics and body composition influence young swimmers' performance.[7,42] In our study, determining partial corelations controlled for *BA* could have eliminated the direct relationship between body dimensions or predicted muscle mass indices and swimming speed, reported in many previous studies.[15,43] Nevertheless, similarly to Moura et al.[38] (boys aged 14 ± 1.8 years), we revealed an association between anthropometric characteristics (*BM*), body composition variables ($m_{\text{m arms}}$), and maximal tethered force of arms measured during 30-second tethered swimming (F_{max}). Morais et al.[44] claim that tethered swimming data is not the best way to measure swimmers ability to generate force in the water. They also stated that swimmers in water strength is correlated with anthropometrics: arm span, hand surface area. Strzała and Tyka[45] noted significant partial correlations with age control between young male swimmers' (age: 16.1 ± 1.09 years) total *BH* and the 100-m front crawl swimming speed ($r = 0.61$; $p < 0.01$). In an investigation by Geladas et al.[15], 100-m freestyle performance of boys (age: 12.78 ± 0.05 years) was highly to very highly correlated ($r = –0.61, –0.65$; $p < 0.01$) with the indices of *BH* and *BM*, as well as several body segments dimensions, but *BA* control was omitted. Arm muscle area measured by Moura et al.[46] was moderately partially correlated (with control for maturation stage) with F_{max} ($r = 0.31$; $p = 0.026$), whereas in our study, $m_{m\ arms}$ turned out highly correlated with F_{max}. Costa et al.[47] comes to the similar conclusions after performing linear regression between arm muscle area and propulsive force of arms, obtained the R^2 value of 0.470, with a significance level of $p < 0.001$. It is worth mentioning that in our study, a relationship was also identified for the indices of *BM*, $m_{m\ trunk}$, $m_{m\ legs}$ with F_{max}, F_{ave}, $F_{decline}$, I_{ave} (Table 1), which showed that young swimmers masculinity level highly determines ability to create the force in the water and *BA* controlling does not excludes this relationship.

A proper level of strength abilities is necessary to provide enough propulsion to successfully compete in sprint swimming, even at the age-group level.[22] In a study by Geladas et al.[15], young male swimmers' (age: 12.78 ± 0.05 years) 100-m front crawl performance was very highly correlated with grip strength ($r = –0.73$; $p < 0.01$), which indicates that upper body strength influence sprint performance of young swimmers. Results of Morouço et al.[23] showed that among adolescent swimmers in 30 s tethered test arms are responsible for ~69% of all of the generated force. The relationship between tethered swimming indices of F_{ave} and 100-m front crawl velocity was stronger in a study by Morouço et al.[20] ($r = 0.61$; $p < 0.05$) in comparison with our results. Unlike Morouço et al.[20], we did not observe significant correlations of F_{max} with swimming speed indices, the reason for that could be controlling for BA in our study and the older group participated in mentioned study (with well-developed strength abilities). Computing partial correlations in our study could have led to exclusion of biological maturation influence on strength abilities and its relation with swimming speed. Taylor et al.[48] imply that the most appropriate moment for increasing anaerobic training is the age of 13 years for both sexes. They observed significant differences in mean force production during tethered swimming between 12 and 13 years and between 14 and 15 years of age. They also stated that in age-group tethered swimming testing, mean force production was reliable and desired in talent identification among 13-year-olds, which is in agreement with observations by Kavouras and Troup.[11] The latter authors, however, reported that the greatest increase in anaerobic capacity occurred at the age of 15 years, but the difference may have been influenced by maturity and body size. It is thought[17] that the significant increase in mean force production at this age results from an improved ability to generate energy via the glycolytic system, with sprint and middle distance events remaining heavily reliant on the glycolytic energy system. In line with our results, Dopsaj et al.[48] assessed the force impulse as a measurable physical characteristic which defines a given quantity of movement. Dopsaj et al.[48] also suggest that in the case of tethered swimming, the force impulse represents the measure/quantity of the implemented pull drive and, as such, reflects the working potential to be involved in nontethered swimming, i.e., free swimming. Cardelli et al.[49]claim that during swimming technique development, improvement is achieved mainly by adjusting longer strokes, which is associated with the ability to orientate motor surfaces in a more efficient way.

Swimming technique has a significant impact on performance of adolescent swimmers.[16,25,31] Klika and Thorland[50] reported that stroke efficiency (*SI*) was among the factors exerting the biggest influence on young males' 100-yard front crawl performance. In a study by De Mello Vitor and Silveira Böhme[7], a regression model involving anaerobic power, swimming index, and critical velocity explained 88% of young swimmers' 100-m front crawl performance. Morais et al.[51] pointed *SI* as the main biomechanical variable determining young swimmers performance at 100-m front crawl. In our study values of SI are higher than in Morais et al.[51], the reason for that could be the age of the participants and thus better technique of older swimmers. Our results are similar to the above mentioned ones because *SI* was highly correlated with V_{total100} and V_{surface}. Reason for lack of correlation between *SR* and V_{surface} in our study is unclear. Increase of *SR* leads to *V* increase but to the certain point when further *SR* raise has no impact on *V* or *V* even decreases[52] Koga et al.[53] explained this phenomenon by continuous decrease of mean hand propulsive force being the effect of *SR* increase. We could state that average impulse per single cycle (I_{ave}) is a good predictor of stroke effectiveness due to it is correlated with *SL* and close to significant related to *SR* and it is not as much affected to bias as *SI*. Changes of kinematic indices at 25-m laps in our study are somehow interesting. It can be observed that the *SR* and $V_{surface}$ decrease in a very similar way. We claim that drop in *SR* beginning from 2[th] lap is caused by the fatigue. Young swimmer were not able to maintain high *SR*. We can say that significant correlation between I_{ave} and *SL* at the last lap confirms that maintaining high *SL* is an effective way of compensating the effect of lower *SR* at the end of the race in our swimmers. We can make an assumption based on our results that the mean force and force impulse generated in each pull and push in a stroke cycle are good predictors of stroke effectiveness because they reflect young swimmers' ability to combine strength with technical properties. Strength abilities are influenced by muscle mass of the swimmer, mainly located in arms and trunk.

Number of participants and test used to measure force generated in the water (tethered swimming) may be considered as limitations of this study.

CONCLUSIONS

A strong relationship between *BM* and muscle mass of body segments and tethered strength swimming indices of F_{ave} young swimmers was observed in our study. The average tethered swimming force was positively correlated with the indices of 100-m front crawl swimming speed.

The kinematic indices of *SL* and *SI* were influenced by average impulse per single cycle, and *SI* was strongly correlated with almost all speed indices of the 100-m front crawl race. We could state that the ability of force generation in a single pull/push performed by young swimmers' arms (I_{ave}) strongly influences the technique effectiveness, defined as *SI* value, and then the swimming speed in a 100-m front crawl race.

Disclosure statement

No potential conflict of interest was reported by the authors.

Authors contribution
All authors read and approved the final version of the manuscript, have contributed significantly to this work and share authorship.

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$\dot{V}O_2$ kinetics and tethered strength influence the 200-m front crawl stroke kinematics and speed in young male swimmers

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Background: The aim of this research was to examine the relationship between the fast component of oxygen consumption developed in 1-min $\dot{V}O_2$ and force indices both measured in tethered swimming test and to assess the influence of the gathered indices on speed and swimming kinematics in 200-m front crawl race.

Methods: Forty-eight male swimmers (aged 13.5 ± 0.9 years old) participated in this study. Testing included 1) 1-min all-out front crawl tethered swimming while oxygen consumption (breath by breath) and tethered forces were measured, 2) 200-m front crawl race-like swimming featuring kinematic analysis, and 3) biological age (*BA*) examination.

Results: During the 1-min all-out tethered swimming test, a linear increase in oxygen consumption was observed. There were moderate to high partial correlations between particular periods of seconds in the 1-min $\dot{V}O_2$: 31–60, 41–60, and 51–60 and F_{max}, F_{ave}, and I_{ave} of tethered swimming, while 41–60 and 51–60 $\dot{V}O_2$ were moderately to highly interrelated with all the swimming speed indices and *SI*. The swimming speed indices significantly interplayed with *SL*, *SI*, F_{max}, F_{ave}, and I_{ave}. Partial correlations were computed with *BA* control.

Conclusion: The ability of reaching a high level of $\dot{V}O_2$ fast is essential for a swimmer's energy production at short- and middle-distance events. Reaching a high level of $\dot{V}O_2$ significantly determines tethered strength and swimming kinematics. The level of $\dot{V}O_2$ influences the maintenance of a proper pulling force and the stroke technique of front crawl swimming in young male swimmers.

KEYWORDS

adolescent swimming, oxygen uptake, tethered swimming, front crawl, biological age, kinematic indices

Introduction

The ability to increase energy production is considered crucial in various sports, even in swimming where high velocities cause relatively high energy cost of movement. Thus, it is necessary among athletes of different age groups to develop either aerobic or anaerobic metabolic pathways of energy production. This begins with proper and adequate training from early prepubertal age and continues further with aging, while controlling the maturation level of the swimmer (Balyi and Way, 2009; Lätt et al., 2009). The contribution of energy pathways in swimming events is varied and depends on the duration of the race (Olbrecht, 2000). The 200-m front crawl, for example, is a race which requires a high involvement of aerobic and anaerobic pathways of energy production (Gastin, 2001).

The aerobic energy system participates in the overall energy production right from the beginning of the all-out effort, and the oxygen uptake almost reaches its maximum level within 60 s of exercising (Gastin and Lawson, 1994; Serresse et al., 1988; Strzała and Tyka 2009). It has been stated that the maximal oxygen uptake ($\dot{V}O_2$ max) assesses the ability in developing and maintaining high speed of sprint swimmers in efforts lasting about 60 s (Ribeiro et al., 2015; Hellard et al., 2018). According to the data presented by Figueiredo et al. (2011), even in 200-m front crawl race, the aerobic pathway engages fast in providing energy for muscle work within half of the race, while at the third (long course) lap, aerobic metabolism provides for around 80% of all energy production. Among swimmers of different age groups, in the 200-m event, the aerobic contribution has been estimated to be 72% (Zamparo et al., 2000) or even 78.6% (Sousa et al., 2011). However, the contribution of the aerobic pathway of energy production in swimming at short and middle distances seems to have been underestimated over the past years (Peyrebrune et al., 2014). Rodriguez et al. (2003) have reported that swimmers not only reached 92.3% of their $\dot{V}O_2\,max$ in the 100-m events but also exhibited $\dot{V}O_2$ kinetics that was significantly faster in the 100-m race than in the 400-m one. Their results highlight the significance of fast oxygen kinetics especially while competing in short races, such as the 100-m ones. Despite the existence of research on the relationship between oxygen consumption and swimming performance, there is a need to refresh (Costill et al., 1985) and further investigate the fast component of $\dot{V}O_2$ kinetics, i.e., the abrupt oxygen delivery to the body in short- to medium-term exercising periods. Moreover, there is a knowledge gap on the influence and dependence of this type of cardiorespiratory efficacy, present in most swimming races, on the ability to generate propulsion force and stroke kinematics.

In swimming, the examination of specific strength abilities is deemed as a key factor when performing an evaluation. For this purpose, swimming tethered tests are often conducted in adults (Kjendlie and Thorsvald, 2006) and swimmers of other age groups (Amaro et al., 2014). Several studies have confirmed a strong relationship between tethered swimming tests (30–120 s) and short-to-middle distance swimming performances (Morouço et al., 2012; Santos et al., 2016).

Biomechanical indices such as stroke length (*SL*), stroke rate (*SR*), and stroke index (*SI*) are significant predictors of young swimmers' performance (Lätt et al., 2009) and are directly related to swimming efficiency (Geladas et al., 2005). The literature reports that strength preparation and a well-developed oxygen system should cause better stroke kinematics in terms of the ability to maintain proper SR and SL along the race (Costill et al., 1985; Sokołowski et al., 2021). Given these premises, the aim of this research was threefold: 1) to examine the relationship between the fast component of oxygen consumption and tethered swimming force production, 2) to examine the relationship between the fast component of oxygen consumption and 200-m front crawl race kinematics, and 3) to assess the relationship between 200-m front crawl race swimming kinematics and performance. It is hypothesized that there would be a significant relationship between oxygen uptake, tethered swimming force, stroke kinematics, and the performance indices.

Materials and methods

Participants

Forty-eight young male swimmers [13.5 ± 0.9 years old; 14.55 ± 1.66 years of biological age (*BA*)] participated in this study. They were recruited as swimmers with the highest performance level in their age category from the Polish region of Krakow and were at the fifth threshold in the Ruiz-Navarro et al. (2022) classification of competitive level. Participants presented swimming levels which resulted in a mean value of 350.32 ± 60.22 FINA points for the 200-m front crawl race. All participants were clinically healthy and held a license from the Polish Swimming Federation. All swimmers had been through 4–5 years of systematic swimming at the time of conducting this research, encompassing at least 10 sessions per week and had taken part in national-level competitions and national swimming championships for their age group.

1-min Tethered swimming test

A tethered swimming test (Figure 1) in a laboratory-controlled environment (temperature and humidity) was conducted. The test consisted of a single bout of 1-min duration of all-out freestyle tethered swimming and was performed in a flume in still water. With due advance notice, the swimmers were asked to rest the day before the test and maintain their daily diet. Before entering the pool, they were informed about the testing procedure and then underwent a 1000-m in-water warm-up, as before any competition. After the warm-up and before the test, they swam for 1 min in the flume at a slow pace, fully equipped with the testing apparatus for adjusting to the testing conditions. At this time, they got the possibility to familiarize with the specific environment of the flume and potential inconveniences of using the breathing apparatus and tethered swimming. After the initial 1 min of familiarization, the scientist conducting the test received feedback from the participant. To signal the beginning and ending of the test, a whistle was used. For the last minutes of warm-up and the test itself, the swimmers were asked to breathe only through the mouthpiece and avoid losing their nose clip. This procedure is similar to their training sessions done using a snorkel. The swimmers were equipped with a respiratory valve system that featured an ergospirometer (Start 2000 MES, Poland). The valve system was attached to a rod-like construction just above the swimmer's head. During the duration of the test, the expired air was analyzed continuously (breath by breath) (Ergo 2000M software MES, Poland) and data were saved for further analysis. This has been proved to be a reliable method of calculating oxygen uptake in swimming (Neiva et al., 2017; Ribeiro et al., 2015; Sousa et al., 2011).

From the collected data, the following indices were computed: 1) average oxygen consumption from the first 30 s of the test (1–30 $\dot{V}O_2$, l·min^{-1}), 2) average oxygen consumption from the last 30 s of the test (31–60 $\dot{V}O_2$, l·min^{-1}), 3) average oxygen consumption from the last 20 s of the test (41–60 $\dot{V}O_2$, l·min^{-1}), 4) average oxygen consumption from the last 10 s of the test (51–60 $\dot{V}O_2$, l·min^{-1}), and 5) oxygen consumption from the total test duration (1–60 $\dot{V}O_2$, l·min^{-1}).

Additionally, the participants wore a nylon waist belt, connected by a 3.7 m steel cable to a load cell (ZPS5-BTU-1kN, Poland) which was fixed on a steel pole (the fixing point is 0.49 m above the water surface). Data were recorded by the load cell at 100 Hz and transferred to a computer software program for further analysis (MAX6v0M software, Poland). Three parameters were calculated over a 60-s recording time: 1) maximum value of force ($F_{\max}$, N); 2) average value of force in the entire test (F_{ave}, N) and in the first and second 30-s parts: $F_{ave\ 0\text{-}30}$, $F_{ave\ 30\text{-}60}$, N; and 3) average impulse per single cycle (I_{ave}, N·s^{-1}) which is defined as the integral of force over a period of time containing all full cycles divided by the number of completed cycles:

$$I_{ave} = \frac{\int_{t_0}^{t_1} F dt}{n} \tag{1}$$

where t_0 is the beginning of the first full cycle and t_1 is the ending of the last full cycle in the 60-s period. Tethered swimming has been described as a reliable method to assess swimming force production (Kjendlie and Thorsvald, 2006; Psycharakis et al., 2011; Amaro et al., 2014).

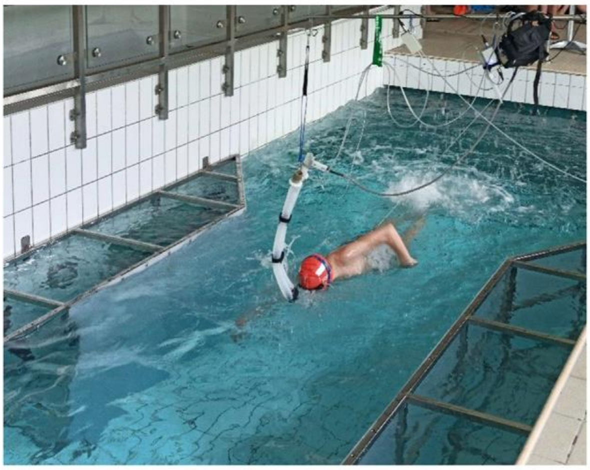

FIGURE 1
1-min tethered swimming test.

200-m Front crawl race

The 200-m all-out test was carried out in a 25-m swimming pool that meets the International Swimming Federation (FINA) requirements. Before the race, the swimmers completed a 1000-m warm-up just like in competitions. Each trial was performed by three to four swimmers in order to mimic competition conditions. The final and split times of each trial were measured with an automatic timing device (Omega, Switzerland; OCP5, StartTime V). All trials were recorded with a camera at 50 Hz framing (GC-PX100BE, JVC, Japan).

The velocity of the part of the race containing the first 10-m start zone as well as start, turn, and finish (which resulted in 115 m) was calculated as V_{STF} (m·s^{-1}). The surface swimming velocity, i.e., the velocity over the effective clean swimming distance (85 m) was deemed V_{surf} (m·s^{-1}). The times for separate sectors were measured when the swimmer's head crosses the imaginary line linking the markers at both sides of the pool. The 200-m front crawl velocity ($V_{total200}$, m·s^{-1}) was defined as 200 divided by the final time of the race. The video footage, placement of the cameras and markers, video analysis, and computation of the basic kinematic parameters were performed analogically to the ones described in the literature (Sokołowski et al., 2021), but in this study, a swimming distance twice as long was considered.

Kinematic parameters

For the kinematic analysis, the stroke rate (*SR*), stroke length (*SL*), and stroke index were calculated. The *SR* was defined as the number of full stroke cycles performed within a unit of time (in

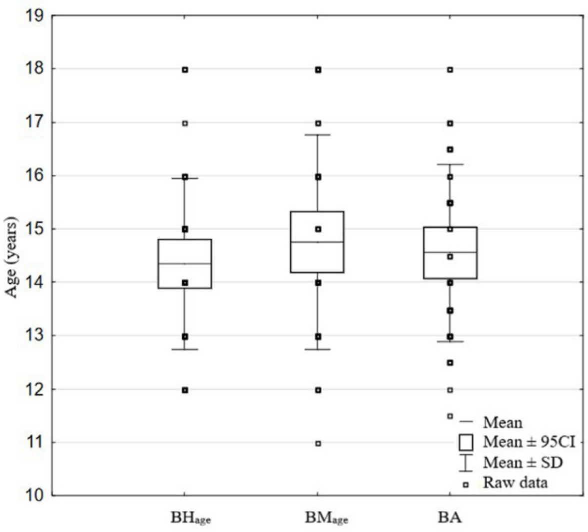

FIGURE 2
Average data of BH_{age}, BM_{age}, and *BA*.

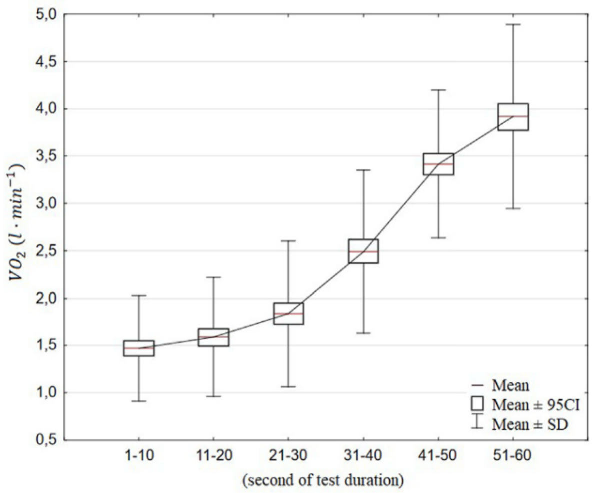

FIGURE 3
Average oxygen consumption of all participants, in 10-s periods, during the 1-min tethered swimming test.

cycles per minute) and was calculated by video analysis of three consecutive stroke cycles (intraclass correlation of 0.99, 95% CI = 0.960–0.997). The *SL* was defined as the horizontal distance that the body travels during a full stroke cycle and was calculated as

$$SL = \frac{v}{SR} \quad (2)$$

where *SL* (in m) is the stroke length, *v* is the swimming velocity, and *SR* is the stroke rate. Finally, the SI was deemed as an overall swimming efficiency estimator and computed as

$$SI = SL \cdot v \quad (3)$$

where *SI* (in $m^2 \cdot s^{-1}$) is the stroke index, *SL* is the stroke length, and *v* is the swimming velocity.

Biological age

Examination of the participants in terms of *BA* was conducted by an experienced anthropologist and calculated as

$$BA = \frac{(BHage + BMage)}{2} \quad (4)$$

where *BHage* is the age obtained from the percentile charts based on the participant's body height and *BMage* is the age obtained from the percentile charts based on the participant's body mass. The growth charts by the Children's Memorial Health Institute, which are standardized and validated for the Polish population, were used (the 50th percentile was used to align the height and mass with age). Additionally, pubertal development was assessed. The Tanner stages based on pubic hair scale were estimated (Bornstein, 2018). The great variety of biological maturation levels in the adolescent groups at the same calendar age causes great differences in muscle mass and aerobic and anaerobic capacities of swimmers. Because of differences in maturation specific water abilities of swimmers and specific testing could be less correlated with swimming performance than simple general tests as isometric force or counter movement jump (Garrido et al., 2012; Strzała et al., 2019). *BA* may cause bias in the statistical analysis and conclusions. The use of partial correlation statistics with age control helps limit the strong influence of *BA* in the effects of statistical calculations. The data used in biological age calculation are presented in Figure 2.

Statistical analysis

The values are presented as mean ± standard deviation. The normality of the data was checked with the Kolmogorov–Smirnov test. In oxygen consumption averaged per 10-s periods, the trend that was most suitable for the gathered data (Figure 3) was identified. The paired-sample t-test was used to compare the values of the average tethered swimming force of the first and second parts of the 1-min tethered swimming test. To identify the relationship between all the variables and swimming velocities in the 200-m front crawl, partial correlations controlled for *BA* were computed for

1) oxygen consumption and force indices;
2) oxygen consumption, swimming speed variables, and kinematic indices; and

TABLE 1 Partial correlations controlled for *BA* between oxygen consumption and force indices from the tethered swimming test.

	F_{max} (N)	F_{ave} (N)	I_{ave} (N·s^{-1})
	250.24 ± 58.39	**74.90 ± 20.63**	**101.93 ± 23.48**
1–30 $\dot{V}O_2$ (l·min^{-1}) 1.68 ± 0.59	0.167	0.053	0.134
31–60 $\dot{V}O_2$ (l·min^{-1}) 3.30 ± 0.76	**0.296***	**0.363****	**0.372****
41–60 $\dot{V}O_2$ (l min^{-1}) 3.65 ± 0.81	**0.395****	**0.494****	**0.502****
51–60 $\dot{V}O_2$ (l min^{-1}) 3.92 ± 0.97	**0.482****	**0.516****	**0.559****
1–60 $\dot{V}O_2$ (l min^{-1}) 2.55 ± 0.59	**0.285***	0.245 $p = 0.054$	**0.290***

*$p \le 0.05$; **$p \le 0.01$.

TABLE 2 Partial correlations controlled for *BA* between oxygen consumption indices from the tethered swimming test, and swimming speed variables and kinematic indices from the 200-m front crawl race.

	$V_{total200}$	V_{surf}	V_{STF}	*S*	*SL*	*SI*
	(m·s^{-1})	(m·s^{-1})	(m·s^{-1})	(cycles·min^{-1})	(m)	(m^2·min^{-1})
	1.40 ± 0.09	**1.34 ± 0.09**	**1.46 ± 0.10**	**41.68 ± 4.52**	**1.93 ± 0.24**	**2.53 ± 0.42**
1-30 $\dot{V}O_2$ (l·min^{-1}) 1.68 ± 0.59	0.187	**0.299***	0.106	0.080	0.076	0.206
31-60 $\dot{V}O_2$ (l·min^{-1}) 3.30 ± 0.76	0.294	0.311	0.288	-0.083	0.206	0.283
41-60 $\dot{V}O_2$ (l·min^{-1}) 3.65 ± 0.81	**0.463***	**0.428***	**0.487***	-0.136	0.310	**0.412***
51-60 $\dot{V}O_2$ (l·min^{-1}) 3.92 ± 0.97	**0.640****	**0.584****	**0.666****	-0.119	**0.393***	**0.539****
1-60 $\dot{V}O_2$ (l·min^{-1}) 2.55 ± 0.59	0.242	0.311 $p = 0.075$	0.201	-0.007	0.155	0.255

*$p \le 0.05$; **$p \le 0.01$.

3) swimming speed variables and kinematic and force indices.

The magnitude of the correlations was determined using the modified scale by Hopkins (2000)—trivial: $r \le 0.1$; low: $0.1 < r \le 0.3$; moderate: $0.3 < r \le 0.5$; high: $0.5 < r \le 0.7$; very high: $0.7 < r \le 0.9$; nearly perfect: $r > 0.9$; and perfect: $r = 1$.

Results

The data shown in Figure 3 represent the increase in oxygen consumption in the 1-min all-out tethered swimming test, in 10-s periods. The analysis of variance revealed significant differences between values measured every 10 s ($F = 164{,}9$, $p < 0.01$). Further trend analysis indicates the linear trend as the best adjusted to the collected data ($F = 289{,}44$, $p < 0.01$).

There were moderate to high correlations between 31–60 $\dot{V}O_2$, 41–60 $\dot{V}O_2$, and 51–60 $\dot{V}O_2$ and all the swimming force indices (F_{max}, F_{ave}, I_{ave}). Low correlations were observed between F_{max}, I_{ave}, and 1–60 $\dot{V}O_2$ (Table 1). A significantly higher average of tethered force was noted in the first 30-s duration of the test: $F_{ave\ 0\text{-}30}$ 85.41 ± 21.41 N *vs* $F_{ave\ 30\text{-}60}$ 67.12 ± 15.22 ($t = 14.77$; $df = 47$; $p \le 0.0000$).

The 41–60 $\dot{V}O_2$ and 51–60 $\dot{V}O_2$ were moderately to highly correlated with all the swimming speed indices and *SI*. V_{surf} was also significantly correlated with 1–30 $\dot{V}O_2$ (Table 2). There was a positive correlation between *SL* and 51–60 $\dot{V}O_2$.

TABLE 3 Partial correlations controlled for *BA* between swimming speed variables and kinematic indices from the 200-m front crawl race and the force indices from the tethered swimming test.

	SR (cycles·min^{-1})	*SL* (m)	*SI* (m^2·s^{-1})	F_{max} (cycles·min^{-1})	F_{ave} (cycles·min^{-1})	I_{ave} (cycles·min^{-1})
$V_{total200}$	0.168	0.325*	0.680**	0.341**	0.321**	0.406**
V_{surf}	0.229	0.301*	0.692**	0.321**	0.408**	0.387**
V_{STF}	0.103	0.337*	0.644**	0.355**	0.411**	0.407**

*$p \le 0.05$; **$p \le 0.01$.

TABLE 4 Average values of oxygen uptake, tethered swimming, and kinematic indices of 200-m front crawl calculated for biological age.

BA (years)/number of participants (n)	51–60 $\dot{V}O_2$ (l·min^{-1})	1–60 $\dot{V}O_2$ (l·min^{-1})	F_{ave} (N)	I_{ave} (N·s^{-1})	*SR* (c·min^{-1})	*SL* (m)	*SI* (m^2·min^{-1})	$V_{total200}$ (m·s^{-1})
11 (n = 1)	2.03	1.33	61.9	89.41	38.88	2.12	2.89	1.43
12 (n = 5)	3.10	1.95	47.31	74.05	45.81	1.72	2.21	1.36
13 (n = 15)	3.42	2.39	65.18	88.31	42.38	1.87	2.45	1.38
14 (n = 5)	3.47	2.38	70.82	98.14	38.62	1.96	2.34	1.31
15 (n = 9)	4.54	2.77	88.6	117.78	41.70	1.99	2.69	1.45
16 (n = 7)	4.41	3.00	82.73	112.44	40.96	1.93	2.49	1.40
17 (n = 4)	4.75	2.91	96.65	123.83	40.09	2.13	2.94	1.48
18 (n = 2)	5.56	3.13	100.95	137.69	40.82	2.08	2.90	1.51

TABLE 5 Average values of kinematic indices for each 50-m lap of 200-m front crawl.

	I 50	II 50	III 50	IV 50
SR (cycles·min^{-1})	42.91 ± 5.49	40.44 ± 4.63	39.99 ± 4.89	43.93 ± 4.87
SL (m)	1.97 ± 0.29	1.92 ± 0.24	1.90 ± 0.24	1.85 ± 0.23
SI (m^2·min^{-1})	2.75 ± 0.54	2.46 ± 0.41	2.40 ± 0.41	2.49 ± 0.42
V_{surf} (m·s^{-1})	1.45 ± 0.11	1.29 ± 0.09	1.26 ± 0.10	1.32 ± 0.09

Regarding the swimming speed and kinematic variables, the strongest relationships were observed between *SI* and $V_{total200}$ and V_{surf} and V_{STF}. The swimming speed was also moderately correlated with *SL*, F_{max}, F_{ave}, and I_{ave} (Table 3).

As a supplement to the results, it was decided to present the level of selected oxygen uptake and strength indicators, measured in the 1-min test, followed by the kinematics of 200-m front crawl in relation to *BA* (Table 4). It could be observed that oxygen uptake and strength abilities continuously improve with higher *BA*. There was also a general increase in values of stroke kinematics through the years of *BA*.

Table 5 shows 200-m front crawl kinematics by each 50-m lap.

Discussion

Regarding the analysis of $\dot{V}O_2$ kinetics, an instantaneous and sudden increase was observed along the 1-min all-out tethered swimming. Despite the increase in $\dot{V}O_2$ which could be characterized as a linear increase, the slopes in both initial and final segments of the 1-min consumption were noticeably lower than the one observed at the middle (Figure 3). Slower oxygen uptake at the beginning of the test may be associated with the use of high-energy phosphocreatine resources and yet low ventilation ($\dot{V}$ *E*); the final slowdown in $\dot{V}O_2$ growth is from reaching a peak and increasing fatigue. This study revealed a significant influence of $\dot{V}O_2$ (mainly 41–60 $\dot{V}O_2$ and 51–60 $\dot{V}O_2$) on 200-m front crawl race swimming speed, swimming kinematic indices, and tethered force indices. A highly developed fast $\dot{O}_2$ supply to working muscles (represented by 51–60 $\dot{V}O_2$) is significantly related to strength ($0.482 \le r \le 0.559$, $p \le 0.01$). This strength in swimming is expressed as the ability to produce propulsive force, which is later translated into higher stroke efficiency and thus better swimming economy (51–60 $\dot{V}O_2$ *vs SI*, r = 0.539, $p \leq 0.01$). Similarly, the higher energy demand connected with 51–60 $\dot{V}O_2$ translated into significantly higher V_{surf} (r = 0.584, $p \leq 0.05$), which depended on proper swimming economy, due to the relationship between V_{surf} and *SI* (r = 0.692, $p \leq 0.01$) and I_{ave} (0.387, $p \leq 0.01$).

This study noted a relationship between 51–60 $\dot{V}O_2$ and the overall performance in 200-m front crawl (r = 0.640, $p \leq 0.01$) which is in tandem with the results of Rodriguez et al. (2003), where a correlation between $\dot{V}O_2$ peak values and the performance at 100 m (r = 0.787, $p \leq 0.05$) and 400 m (r = 0.752, $p \leq 0.05$) was observed. The reason for a weaker correlation in our study could be the longer period considered for the mean $\dot{V}O_2$ calculation. We used 10-s periods, while Rodriguez et al. (2003) used 5-s periods. The breath-by-breath acquisition technique can induce a significant variability on acquired $\dot{V}O_2$ values, and different sampling periods might produce different outcomes. Moreover, our quite restrictive statistical calculations (including *BA* control) could also play a role in that difference. In comparison to the results of Sousa et al. (2011), which showed a positive correlation between 200-m front crawl swimming speed and $\dot{V}O_2$ peak (r = 0.69, $p = 0.03$), our partial correlation was somewhat slightly lower (r = 0.640, $p \leq 0.01$). Nevertheless, these researchers found high $\dot{V}O_2$ values right after the first 50 m that swimmers could almost maintain for the 200-m effort. Researchers have put forward that the need for oxygen in the muscles triggers an instantaneous and sudden increase in O_2 uptake from the very beginning of the exercise (Ribeiro et al., 2015; Hellard et al., 2018). Maybe the highest peak of O_2 uptake could be reached even faster in our study and show faster kinetics in young athletes, but because it is in swimming, the aim of racing (also through the test) is to withstand the pace as much as possible until the end of the race. Nevertheless, in our research, we recorded a positive distribution of average tethered swimming force ($F_{ave\ 0\text{-}30}$ 85.41 ± 21.41 N *vs* $F_{ave\ 30\text{-}60}$ 67.12 ± 15.22 N). The question here is how speedily and individually for a competitor, should a race be open to young 13-year-old swimmers in order to allow for the proper engagement of the fast component of oxygen consumption. It is known that positive pacing, or rather starting a race too speedily, can cause excessive fatigue, low oxygen distribution, and lactic acidosis in the skeletal muscles, which slow down energy production in the aerobic pathway. It may also be due to fatigue of the chest breathing muscles during the second part of the 200-m distance (Gastin and Lawson, 1994).

It can be stated that for high aerobic capacity, the fast development of high level of O_2 supply is crucial while performing middle distance events such as the 200-m front crawl. For this purpose, the 1-min tethered swimming test seems to be appropriate in examining the ability to supply O_2 to the swimmer's muscles to produce propulsion. Serresse et al. (1988) who examined the maximum 90-s ergocycle test observed that the highest $\dot{V}O_2$ values occurred at about 60 s into the test. Similar to our study, their results have shown a linear increase in oxygen uptake up to 60 s into the test. Gastin and Lawson (1994) stated that 30–60 s of maximum effort could be enough to reach up to 90% of athletes' $\dot{V}O_2$ max. Ribeiro et al. (2015) claimed that if the majority of the swimming races are 50, 100, and 200 m, performed at high speeds, examining the $\dot{V}O_2$ max at low intensities has limited application in the evaluation of the swimmer's conditioning. Alves et al. (2011) suggested that faster kinetics during the initial phase of $V\dot{O}_2$ max testing is directly related to a better performance at middle-distance events in swimming. Based on this reasoning, one could suggest that middle-distance swimmers should undergo long, high-intensity aerobic repeated sprints in training sessions.

Regarding tethered force production, in the present study, a significant positive correlation was found between all indices and 200-m front crawl speed ($0.321 \leq r \leq 0.411$, $p \leq 0.01$). Other authors have reported similar findings: Santos et al. (2016) have noted a positive correlation (0.61, $p < 0.001$) between the peak force of the 2-min tethered swimming test and clean velocity of 200-m front crawl race, while Morouço et al. (2012) showed a very strong relationship between average pulling force, peak force, and 200-m front crawl velocity (r = 0.94 and r = 0.93, respectively, $p < 0.01$). Again, controlling for *BA* and longer test duration could be the reasons for weaker correlations in our study.

Our study showed great diversity in *BA* (Figure 2; Table 4). It is therefore a practical example of emphasizing the need for each trainer to adapt their training in relation to the *BA* of their swimmers. If this is the case, even the most gifted swimmers with delays in relation to *BA* are often frustrated by worse athletic performance when compared to their calendar peers, and in consequence, they overtrain trying to catch up to the others, get disappointed, then quit their swimming training. On the other hand, swimmers more advanced in relation to *BA* have the potential to develop through more individualized, intense training.

Based on the high correlation between 51–60 $\dot{V}O_2$ and *SI* found in the present study (r = 0.539, $p \leq 0.01$), we can state that peak oxygen consumption determined the rate of transfer from chemical energy to mechanical energy, thus leveling up the stroke kinematics of the swimmers. This finding backs up the results by Sánchez and Arellano (2002), where the *SI* was found to be higher in international-level swimmers than their national-level counterparts in all swim strokes. Barbosa et al. (2013) proposed a multidisciplinary model of swimming performance predictors where the *SI* plays a significant role. In a study by Costill et al. (1985), the predictability of $\dot{V}O_2\ max$ at freestyle was reported to increase significantly when the *SI* was included in the multiple regression analysis of an approximate 400-m swim. The multiple regression models prepared by Mezzaroba and

Machado (2013) revealed that in young male swimmers, the *SI* at the 200-m front crawl race explained 76% of the performance. In the study by Nasirzade et al. (2015), 200-m front crawl performance of young swimmers was strongly related to the *SL* and *SI* (r = −0.79 and r = −0.72, $p < 0.01$, respectively). The mentioned studies are in tandem with our results where *SI* presented the highest positive correlation with all 200-m front crawl variables ($0.644 < r \leq 0.692$, $p \leq 0.01$). This very high percentage of share of the *SI* in performance in the abovementioned studies is also because of its link to performance itself, because the stroke index contains the speed (according to the formula: $SI = SL \cdot v$).

The present study, analyzing the relationship between the aerobic conditioning level, force production, and stroke kinematics is in accordance with the one study found in the literature on this matter, where Costill et al. (1985) identified interrelationships between oxygen uptake, energy cost of swimming, and stroking economy (*SI*). In our study, we found moderate to high correlations between 31–60 $\dot{V}O_2$, 41–60 $\dot{V}O_2$, and 51–60 $\dot{V}O_2$ and $F_{\max}$, F_{ave}, and I_{ave}. Low correlations were observed between $F_{\max}$, I_{ave}, and 1–60 $\dot{V}O_2$. It could be stated that the ability to generate the pulling force is directly and positively related to the fast O_2 supply which is linked with the endurance of the swimmer in terms of aerobic energy production and also lactate utilization or turnover to ATP (Greenwood et al., 2008).

Conclusion

In the 1-min all-out effort, a sudden increase in oxygen uptake was observed, with swimmers reaching high levels of $\dot{V}O_2$ by the end of the tethered test. This fast ability of reaching high $\dot{V}O_2$ and trainability of this physiological variable is essential for fitting an appropriate pacing in middle-distance racing and must be an important aspect of 13-year-old swimmers' conditioning and of the older age groups too, in relation to their *BA*. Furthermore, it is suitable for the physiological preparation for 200-m front crawl performance and can be useful as a predictor of the swimmer's endurance. The high intensity $\dot{V}O_2$ testing used in the present study is appropriate for predicting sprint (100-m) and middle-distance swimming events performed at high speeds. There is a relationship between the fast-developed 1-min high-level oxygen uptake and the tethered strength abilities and high-speed swimming. The fast O_2 supply is crucial for maintaining a proper pulling force and stroke technique.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the Regional Medical Chamber in Cracow; decision number: 94/KBL/OIL/2020. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

KS collected data, performed statistical analysis, and wrote the manuscript. RB cowrote the manuscript. TB reread and corrected the manuscript. MS cowrote the manuscript and collected data.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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