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Froude Efficiency and Velocity Fluctuation in Forearm-Amputee Front Crawl: Implications for Para Swimming Classification

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ABSTRACT

O'DOWD, D. N., L. HOGARTH, B. BURKETT, C. OSBOROUGH, D. DALY, R. SANDERS, and C. PAYTON. Froude Efficiency and Velocity Fluctuation in Forearm-Amputee Front Crawl: Implications for Para Swimming Classification. *Med. Sci. Sports Exerc.*, Vol. 55, No. 7, pp. 1296–1306, 2023. **Purpose:** The impact of physical impairment on Froude efficiency and intracyclic velocity fluctuation in Para swimmers is not well documented. Identification of differences in these variables between disabled and nondisabled swimmers could help develop a more objective system for assigning Para swimmers to classes for competition. This study quantifies Froude efficiency and intracyclic velocity fluctuation in unilateral forearm-amputee front crawl swimmers and evaluates associations between these variables and performance. **Methods:** Ten unilateral forearm-amputee swimmers completed front crawl trials at 50- and 400-m pace; three-dimensional video analysis provided mass center, and wrist and stump velocities. Intracyclic velocity fluctuation was calculated as follows: 1) maximum–minimum mass center velocity, expressed as percent of mean velocity, and 2) coefficient of variation in mass center velocity. Froude efficiency was the ratio between mean swimming velocity and wrist plus stump velocity during each segment's respective 1) underwater phase and 2) propulsive underwater phase. **Results:** Forearm amputees' intracyclic velocity fluctuation (400 m: 22% ± 7%, 50 m: 18% ± 5%) was similar to published values for nondisabled swimmers, whereas Froude efficiencies were lower. Froude efficiency was higher at 400-m (0.37 ± 0.04) than 50-m pace (0.35 ± 0.05; $P < 0.05$) and higher for the unaffected limb (400 m: 0.52 ± 0.03, 50 m: 0.54 ± 0.04) than the residual limb (400 m: 0.38 ± 0.03, 50 m 0.38 ± 0.02; $P < 0.05$). Neither intracyclic velocity fluctuation nor Froude efficiency was associated with swimming performance. **Conclusions:** Froude efficiency may be a valuable measure of activity limitation in swimmers with an upper limb deficiency and a useful metric for comparing swimmers with different types and severity of physical impairment. **Key Words:** PARALYMPICS, IMPAIRMENT, LIMB DEFICIENCY, PROPULSION, PERFORMANCE

The Paralympics are the peak of international competition for athletes with a disability. The difference between Olympic and Paralympic events is the use of a classification system to group Para athletes for equitable competition, with the aim of limiting the impact of impairment on the competition outcome. World Para Swimming currently utilizes a functional classification system to group swimmers with physical impairments into 1 of 10 sport classes (1). In this system, Para swimmers with different physical impairments compete in the same class if they are deemed to be limited in swimming to the same degree. Swimmers' impairment is assessed using physical bench tests and an in-water technical assessment (1), and they are classified via a points-based system, with lower classes representing those who are more limited in swimming. Eligible physical impairments include hypertonia, ataxia, athetosis, impaired muscle power, impaired passive range of motion, short stature, lower limb length difference, and limb deficiency (1).

Research has demonstrated that the current Para swimming classification system fails to delineate performance between some adjacent classes. Evidence demonstrates that there are

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issues with the weighting and aggregation of ordinal-scale measures and that the grouping of swimmers with different types of physical impairment results in unequal or dissimilar activity limitation (2,3). In response to these criticisms, the International Paralympic Committee has instructed the development of new evidence-based classification systems in Para sport (4). An important step toward achieving this in Para swimming is to examine the impact of impairment type and severity on the determinants of swimming performance (5).

Performance is dependent on a swimmer's ability to produce propulsive forces and reduce drag forces from the water (3). Movement of a swimmer's limbs and torso causes these forces and consequently the fluctuating forward velocity of the swimmer's mass center. Front crawl involves alternating movements of the upper limbs, where one recovers above the water while the other pulls below the water, although both can be in the water at the same time for at least part of the cycle. The coordination of the two upper limbs is often categorized according to the time delay between their propulsive phases (6): Catch-up describes a time delay between propulsive phases, Opposition describes continuous propulsive actions with one limb beginning its propulsion just as the other ends, and superposition describes coordination involving an overlap of the propulsive phases (7).

Importantly, the hand plus forearm segment contributes approximately 85% of total propulsion for nondisabled front crawl swimmers (8). In Para swimming, recent research has demonstrated that the length of the forearm and of the hand were the most important predictors of 100-m freestyle performance in swimmers with limb deficiencies (2). Because Para swimmers with unilateral forearm amputation are without these important propelling limb segments on one side, they may be disadvantaged in their potential to produce propulsion.

Computational fluid dynamics analysis of a unilateral forearm amputee predicted that swimmers can produce propulsion with their affected limb at swimming speeds of around 1.0 $\text{m}\cdot\text{s}^{-1}$. However, the effectiveness of the residual limb at generating propulsion decreases with increased swimming speed (9), unless the residual limb angular velocity is increased proportionally. In support, field-based research found that unilateral forearm-amputee swimmers produced lower mean tether forces than nondisabled swimmers during maximal tethered front crawl swimming (10). Both studies indicate that the potential for unilateral forearm-amputee swimmers to produce propulsion and thus maintain velocity with the residual limb is compromised. The strategy of rotating the residual limb through the water faster than the unaffected limb may help to compensate for the absent hand and forearm but could have a negative impact on the swimmer's intracyclic velocity fluctuation and their Froude efficiency. Intracyclic velocity fluctuation is a measure of how much a swimmer's velocity, in the swimming direction, changes within an upper limb cycle. Froude efficiency is defined as the proportion of the external mechanical power produced by the swimmer that is used to overcome hydrodynamic resistance (11). Both of these variables have been associated with the energy cost of swimming in nondisabled swimmers (11–13), but the association between the two is yet to be established.

Swimming velocity is often assessed using a "velocimeter" device attached to a fixed point on the body (usually the hip). The main limitation of this method is that the instantaneous velocity of the hip does not accurately match that of the swimmer's mass center (14–16). Because swimming involves three-dimensional (3D) movements, a more accurate method of tracking mass center movement is via 3D motion analysis. Intracyclic velocity fluctuation is typically quantified either using the coefficient of variation of velocity within an upper limb cycle (17–22) or the intracycle velocity range expressed as a percent of the mean cycle velocity (13,23,24), hereafter referred to as ICVF_{CV} and $\text{ICVF}_{\%}$, respectively. No study has compared these two methods, but it would be useful to do this to facilitate comparison between studies. Including both methods, intracyclic velocity fluctuation in nondisabled front crawl swimmers ranges from 6% to 24% (13,17–24), with elite swimmers exhibiting lower values than nonelite swimmers (18,20). Of those studies that analyzed mass center motion of nondisabled swimmers, two used a maximal effort 200-m swim and reported an $\text{ICVF}_{\%}$ of ~22% for men of national and international levels (23) and an ICVF_{CV} of ~20%–24% for men of international level (25), and the third reported an ICVF_{CV} value of 7% for well-trained men tested at subanaerobic threshold pace (13).

Of the few studies examining intracyclic velocity fluctuation in Para swimmers, one reported no difference in ICVF_{CV} between Para and nondisabled swimmers (22). Other studies have found no association between ICVF_{CV} and swimming-specific impairment severity (26), a positive association between ICVF_{CV} and swimming speed in one female arm-amputee swimmer (27), and a tendency for greater ICVF_{CV} in swimmers with more severe swimming-specific impairment (28). Because these studies grouped different impairments together or examined a single swimmer, the impact of impairment type on intracyclic velocity fluctuation has not been established. Nonetheless, one study (28) highlighted that the greatest ICVF_{CV} (36%) was exhibited by a unilateral forearm-amputee swimmer. The only authors to assess intracyclic velocity fluctuation in a homogeneous group of Para swimmers reported an $\text{ICVF}_{\%}$ of 35% for unilateral forearm-amputees swimming at front crawl at 1.09 ± 0.13 $\text{m}\cdot\text{s}^{-1}$ (29). This study was limited in that it utilized a velocimeter and assessed front crawl performed using the upper limbs only.

Measuring a swimmer's power output and hydrodynamic resistance noninvasively, to derive Froude efficiency, is extremely challenging. Thus, in the past 15 yr, researchers have developed new models for estimating efficiency based on measures of swimming velocity and upper limb velocity (13,30–36) or swimming velocity and hand propulsion (37,38). These models generally do not consider the internal work done to accelerate and decelerate the limbs with respect to the body mass center. Thus, they provide an estimate of Froude efficiency (η_F) rather than propelling efficiency (η_P), which requires the swimmer's total power output (internal plus external) to be known (11). Swimming efficiency has been defined

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and calculated in various ways in the literature, so differences between methods must be considered when comparing values between studies. For a detailed discussion of swimming efficiency see (11).

Efficiency models that utilize hand propulsion (37,38) are computationally more sophisticated than those that use upper limb velocity. However, they require calculation of hand hydrodynamic forces from lift and drag coefficients; this precludes their use in analysis of limb deficient swimmers. The best efficiency model based on upper limb velocity computes the ratio of the mean velocity of the swimmer's mass center to the mean resultant velocity of the hand while underwater (34). This method is likely superior to simpler models that only estimate hand velocity indirectly from 2D motion analysis or assume the swimmer's velocity and rotational velocity of the upper limbs are constant (30–33). Using this approach (34), the Froude efficiency of well-trained nondisabled male front crawl swimmers was reported as 0.43 at 1.57 and 0.41 at 1.33 $m \cdot s^{-1}$ (34), 0.40 at ~1.08 $m \cdot s^{-1}$ (13), and as increasing from 0.41 to 0.47 as test speeds decreased from ~1.57 to 1.29 $m \cdot s^{-1}$ (35).

Froude efficiencies ranging from 0.25 to 0.63 have been reported for nondisabled front crawl swimmers (30–36,38,39). Efficiency improves when propelling surface area is increased using hand paddles (38), is greater in faster than slower swimmers (36), and decreases with advancing age (32). In a group of front crawl swimmers with various physical impairment types, Froude efficiency was estimated to be 0.31 (28). It is yet to be reported for any homogeneous group of physically impaired swimmers, but doing so may provide a useful measure of the impact of impairment. For swimmers with asymmetric impairments, such as unilateral partial arm-amputee swimmers, it is pertinent to consider the Froude efficiency of each upper limb independently to gain some insight into how the affected limb compromises the overall Froude efficiency. This is possible using the resultant hand speed method (34), providing that there is no overlap in the propulsive phase of each upper limb.

There is little information on the impact of physical impairments on mass center velocity profiles and Froude efficiency in highly trained swimmers. An investigation into how these variables explain activity limitation in Para swimmers and how they differ compared with nondisabled swimmers would have implications for evidence-based classification in Para swimming. For instance, these measures would likely prove useful in describing the activity limitation of Para swimmers with dysmelia, whose proximal rather than distal limb segments are affected, or to evidence the effect of event distance on the varied contributions of limb segments to swim performance (2,40). Therefore, the current study aimed to quantify the impact of a specific impairment, unilateral forearm amputation, on intracyclic velocity fluctuation and Froude efficiency during sprint and distance-paced front crawl swimming, and to examine associations between these variables. Because of the link between upper limb velocity and propulsion, the backward velocity of the hand and stump relative to the global, pool-fixed, reference frame will also be quantified. We hypothesize that 1) the Froude efficiency of unilateral forearm amputees will be lower than values reported for nondisabled swimmers, 2) Froude efficiency will be lower for the residual limb than the unaffected limb, 3) intracyclic velocity fluctuation of forearm amputees will differ from values reported for nondisabled swimmers, and 4) associations will exist between Froude efficiency, intracyclic velocity fluctuation, upper limb velocity, and swimming velocity in forearm amputees.

METHODS

Participants. Ten well-trained unilateral forearm-amputee swimmers (eight female and two male) took part in this study (age, 16.8 ± 3.3 yr; height, 1.68 ± 0.09 m; body mass, 63.9 ± 14.2 kg). All swimmers were congenital amputees at the elbow and held an international classification; nine competed in the S9 class, and one (male) competed in the S8 class because of an additional minor impairment in one of his lower limbs. Their mean best time for long course 50-m front crawl was 33.1 ± 3.1 s, which corresponded to 87.1% ± 6.4% of the relevant Para swimming world record at the time of testing. The lead author's University Ethics Committee granted ethical approval, and all participants provided written informed consent or parental written consent was obtained for minors.

Test protocol. Participants completed a 600-m warm-up followed by two 25-m front crawl trials from a push start separated by 3 min. One trial was at the individual's 50-m race pace and the other at their 400-m race pace, each at a predetermined target time based on their season's best race time. Two experienced timekeepers manually recorded all trials, and trials not within ±2% of the target pace were repeated after a 3-min rest. Trial order was counterbalanced between two test groups, and participants were instructed not to take a breath as they swam through a 10-m test zone containing a calibrated performance volume.

Data collection. Calibration of the performance volume was undertaken using a 6.75-m^3 frame (4.5 m × 1.0 m × 1.5 m) with orthogonal axes for the swimming direction (X), the lateral direction (Y), and the vertical direction (Z). Half the frame sat above the water, and half sat below the water. Ninety-two spheres of known location were distributed throughout the volume, with 46 above and 46 below the water. Six stationary, synchronized video cameras (JVC KY32 CCD) operating at 50 Hz with a shutter speed of 1/120 s recorded each trial within the performance volume. Four cameras were located below the water, and two were located above. Camera and calibration frame positions have been reported previously (23).

Data processing. A 13-segment model of the body was defined by 18 body landmarks as previously reported (23,41), with the exception of the residual limb, which was marked at the elbow and the most distal end point. Landmarks were marked with black waterproof oil and wax-based cream to aid digitization. The estimated locations of joint centers or segment end points underlying these landmarks were manually digitized at a sampling rate of 50 Hz (SIMI Motion 9.2; SIMI Reality Motion Systems GmbH, Unterschleißheim, Germany). A DLT algorithm transformed 2D image coordinates to 3D real-world coordinates, which were then smoothed via a second-order low-pass Butterworth filter with a cutoff frequency of 6 Hz (37).

Whole-body center of mass. The elliptical zone method was used to establish personalized body segment parameter data for each participant (42) using digital images from each swimmer standing in the anatomical position, in both frontal and sagittal planes. Body segment outlines were then manually traced on the images and segment volumes obtained using custom software (42). Segment densities reported by Dempster (43) were applied to estimate segment mass and mass center locations from which the swimmer's whole-body center of mass position was calculated. The accuracy and reliability of this method have been reported previously for the participants in this study (44).

Data analysis. One and a half upper limb cycles were analyzed to include consecutive water entries of both the hand and stump. Eight variables were calculated from each swimmer's horizontal (*x*-component) mass center velocity during one upper limb cycle at 50- and 400-m pace: 1) mean swimming velocity (V_{MEAN}), mean velocity in the upper limb cycle; 2) maximum velocity (V_{MAX}), highest instantaneous velocity in the upper limb cycle; 3) minimum velocity (V_{MIN}), lowest instantaneous velocity in the upper limb cycle; 4) relative maximum velocity ($V_{\mathrm{MAX}\%}$), $V_{\mathrm{MAX}}/V_{\mathrm{MEAN}} \times 100$; 5) relative minimum velocity ($V_{\mathrm{MIN}\%}$), $V_{\mathrm{MIN}}/V_{\mathrm{MEAN}} \times 100$; 6) absolute intracyclic velocity fluctuation ($\mathrm{ICVF}_{\mathrm{ABS}}$), $V_{\mathrm{MAX}} - V_{\mathrm{MIN}}$; 7) relative intracyclic velocity fluctuation ($\mathrm{ICVF}_{\%}$), $[V_{\mathrm{MAX}} - V_{\mathrm{MIN}}]/V_{\mathrm{MEAN}} \times 100$; and 8) coefficient of variation of intracyclic velocity ($\mathrm{ICVF}_{\mathrm{CV}}$), $V_{\mathrm{SD}}/V_{\mathrm{MEAN}} \times 100$, where V_{SD} is the standard deviation of the intracyclic velocity.

The upper limb cycle was divided into four phases for both sides (13,41): 1) glide, from finger/stump entering water to its first backward movement relative to the global reference frame; 2) pull, from end of glide to vertical alignment of the finger/stump with the glenohumeral joint; 3) push, from end of pull to last backward movement of the finger/stump relative to the global reference frame; and 4) recovery, from end of push to next finger/stump entry. Each swimmer's mean mass center velocity during the glide, pull, and push phases of the residual limb and unaffected limb were expressed as a percentage of their mean swimming velocity (V_{MEAN}) at both paces, hereafter termed relative swimming velocity. In addition, the mean backward velocity of the hand and stump, relative to the global reference frame, was calculated in their pull and push phases, hereafter termed segment backward velocity. The magnitude of the instantaneous resultant velocity of the wrist and stump, relative to a local reference frame fixed at the swimmer's center of mass, hereafter termed resultant segment speed, was calculated by subtraction of the segment velocity vector from the whole-body mass center velocity vector.

Mean resultant segment speed was calculated for the wrist and for the stump during the respective segment's entire underwater phase (resultant segment speed underwater; $V\mathrm{wrist}_{\mathrm{UW}}$, $V\mathrm{stump}_{\mathrm{UW}}$) and for their propulsive (pull + push) underwater phase (resultant segment speed propulsive; $V\mathrm{wrist}_{\mathrm{PROP}}$, $V\mathrm{stump}_{\mathrm{PROP}}$). Froude efficiency was calculated over an upper limb cycle using equation 1 (34):

$$\text{Froude efficiency} = V_{\mathrm{MEAN}}/(V\mathrm{wrist}_{\mathrm{UW}} + V\mathrm{stump}_{\mathrm{UW}}) \qquad [1]$$

Froude efficiency for the unaffected limb and residual limb were obtained using equations 2 and 3, respectively:

$$\text{Froude efficiency unaffected limb} = V_{\mathrm{MEAN\_PROP}}/V\mathrm{wrist}_{\mathrm{PROP}} \qquad [2]$$

$$\text{Froude efficiency residual limb} = V_{\mathrm{MEAN\_PROP}}/V\mathrm{stump}_{\mathrm{PROP}} \qquad [3]$$

where $V_{\mathrm{MEAN\_PROP}}$ is the mean velocity of the swimmer's mass center during the respective segment's propulsive phases.

Statistical analysis. IBM SPSS Statistics 27 software was used to analyze the data. Statistically significant differences were accepted at $\alpha < 0.05$. All data were found to be normally distributed using the Shapiro–Wilk test. To test for differences in swimming velocity variables and Froude efficiency between the 50- and 400-m pace, paired-samples *t*-tests were used and Cohen's *d* was calculated as a measure of the effect size. Three-way repeated-measures ANOVAs were conducted to test for differences in 1) relative swimming velocity between three phases, two paces, and two limb sides, and 2) segment backward velocity between two phases, two paces, and two limb sides. Two-way repeated-measures ANOVAs were conducted to test for differences in 1) resultant segment speed underwater between two paces and two limb sides, 2) resultant segment speed propulsive between two paces and two limb sides, and 3) Froude efficiency between two paces and between the unaffected and residual limb. Multiple comparisons were made using Bonferroni corrected *post-hoc* pairwise comparisons and partial eta squared (η_p^2) was calculated as a measure of the effect size. If data did not pass Mauchly's test of sphericity ($P < 0.05$), a Greenhouse–Geisser correction was applied. To determine the strength of associations between variables, Pearson correlations were calculated. A correlation was considered significant if $P < 0.05$ and defined as weak (<0.3), moderate (0.3–0.6), or strong (>0.6).

RESULTS

Intracyclic velocity fluctuation. Discrete variables describing the swimmers' velocity changes within a cycle are shown in Table 1; mass center velocity throughout one upper limb cycle is presented as an ensemble average in Figure 1. Variables V_{MEAN} ($t_9 = 3.63$, $P \leq 0.01$, $d = 1.15$), V_{MAX} ($t_9 = 2.81$, $P < 0.05$, $d = 0.89$), and V_{MIN} ($t_9 = 4.31$, $P \leq 0.01$, $d = 1.36$) were lower in the 400-m pace than the 50-m pace, and $\mathrm{ICVF}_{\mathrm{CV}}$ was lower in 50-m than 400-m pace ($t_9 = -2.66$, $P < 0.05$, $d = -0.84$). $\mathrm{ICVF}_{\mathrm{ABS}}$ ($t_9 = -0.78$, $P > 0.05$, $d = -0.25$), $V_{\mathrm{MAX}\%}$ ($t_9 = -2.05$, $P > 0.05$, $d = -0.65$), $V_{\mathrm{MIN}\%}$ ($t_9 = 1.29$, $P > 0.05$, $d = 0.41$), and $\mathrm{ICVF}_{\%}$ ($t_9 = -2.07$, $P = 0.068$, $d = 0.66$) did not differ between the 50-m and 400-m pace.

Relative swimming velocity. Mean swimming velocities during glide, pull, and push of the unaffected and residual

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TABLE 1. Swimming velocity variables for 10 unilateral forearm-amputees swimming front crawl at 50-m and 400-m pace (mean ± SD).

	50-m Pace	400-m Pace
Mean swimming velocity (m·s^{-1})	1.31 ± 0.15	1.17 ± 0.09[a]
Upper limb cycle time (s)	1.28 ± 0.22	1.47 ± 0.22[a]
Maximum velocity (m·s^{-1})	1.44 ± 0.14	1.32 ± 0.11[a]
Minimum velocity (m·s^{-1})	1.20 ± 0.13	1.06 ± 0.08[a]
Absolute intracyclic velocity fluctuation (m·s^{-1})	0.24 ± 0.06	0.26 ± 0.09
Relative maximum velocity (%)	110 ± 3	112 ± 5
Relative minimum velocity (%)	92 ± 2	90 ± 3
Relative intracyclic velocity fluctuation (%)	18 ± 5	22 ± 7
Coefficient of variation of intracyclic velocity fluctuation (%)	5 ± 1	6 ± 1[a]

[a] Significant difference between paces.

limb are presented for both paces in Figure 2. An interaction effect was found between phase and limb side on relative swimming velocity ($F_9 = 71.20$, $P \leq 0.01$, $\eta^2_{\mathrm{p}} = 0.89$). No other interactions were found ($P > 0.05$). For the residual limb, relative swimming velocity decreased from glide to pull and from glide to push ($P < 0.01$), but for the unaffected limb relative swimming velocity increased from glide to push and from pull to push ($P < 0.001$).

Segment backward velocity. Figure 3 presents the mean backward velocity of the stump and hand, relative to the global reference frame, during the pull and push phases of the unaffected and residual limb at the 50- and 400-m pace. There was a main effect of pace ($F_9 = 16.83$, $P \leq 0.01$, $\eta^2_{\mathrm{p}} = 0.65$) and an interaction between limb side and phase on segment backward velocity ($F_9 = 73.95$, $P \leq 0.01$, $\eta^2_{\mathrm{p}} = 0.89$). No other interactions were found ($P > 0.05$). Backward velocity was greater at 50-m than 400-m pace ($P < 0.001$). For the hand, backward velocity was greater in

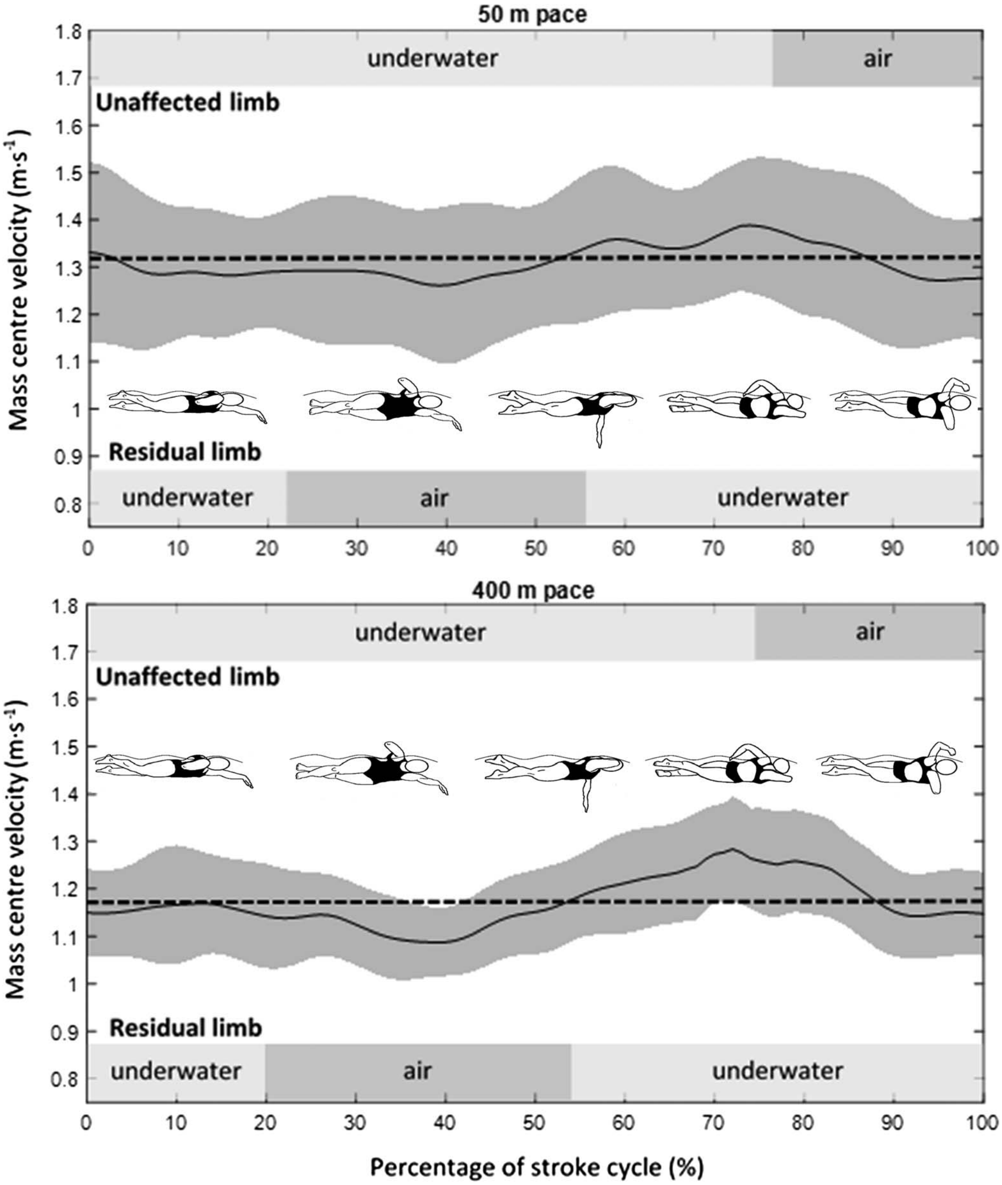

FIGURE 1—Horizontal mass center velocity during an upper limb cycle. Black solid lines (*gray shading*) represent the mean (±1 SD) for the 50-m pace (*top image*) and 400-m pace (*bottom image*). 0% is finger entry on the unaffected side, and 100% is the next finger entry on the same side. *Dashed lines* represent the mean velocity of the mass center during an upper limb cycle.

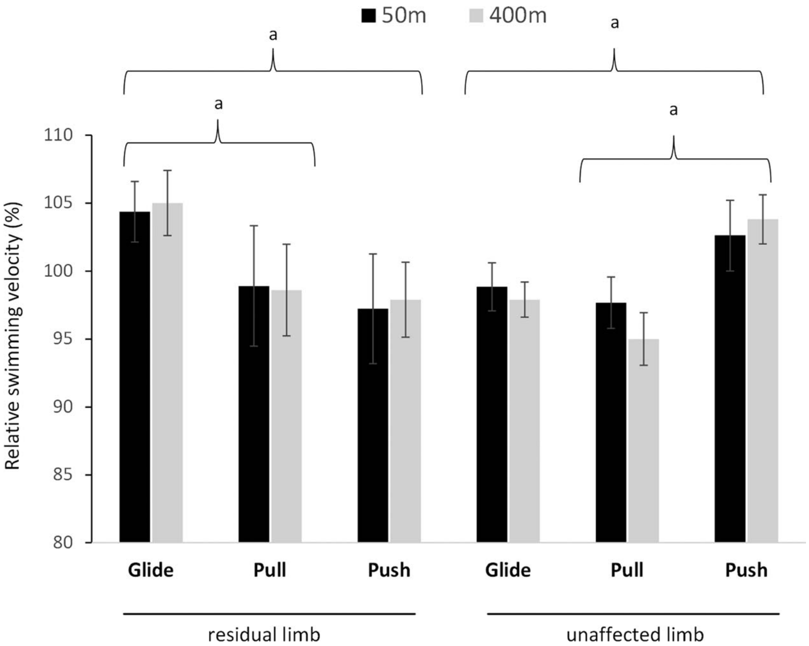

FIGURE 2—Data for 10 unilateral forearm-amputees swimming front crawl. Mean horizontal velocity of the swimmer's mass center during the glide, pull, and push phases of the unaffected and residual limb at 50-m (*black bars*) and 400-m pace (*gray bars*), expressed relative to mean swimming velocity (mean ± SD). [a]Significant difference between phases.

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the push than pull phase ($P < 0.05$), whereas for the stump, backward velocity was lower during the push than the pull phase ($P < 0.001$). For the pull phase, backward velocity was greater for the stump than the hand ($P < 0.001$), whereas for the push phase, backward velocity did not differ between the limb sides ($P > 0.05$).

Resultant segment speeds and Froude efficiency. Resultant segment speed of the wrist and stump during the upper limb cycle is presented as an ensemble average in Figure 4. Mean values for resultant segment speed underwater, resultant segment speed propulsive, and Froude efficiencies are presented in Table 2. A main effect of pace ($F_9 = 17.89$, $P \leq 0.01$, $\eta_p^2 = 0.67$) and limb side ($F_9 = 9.07$, $P < 0.05$, $\eta_p^2 = 0.50$) were found for resultant segment speed underwater. No interaction effects were found ($P > 0.05$). Resultant segment speed underwater was lower at the 400-m than 50-m pace and lower for the stump than the wrist ($P < 0.001$). For resultant segment speed propulsive, a main effect of pace

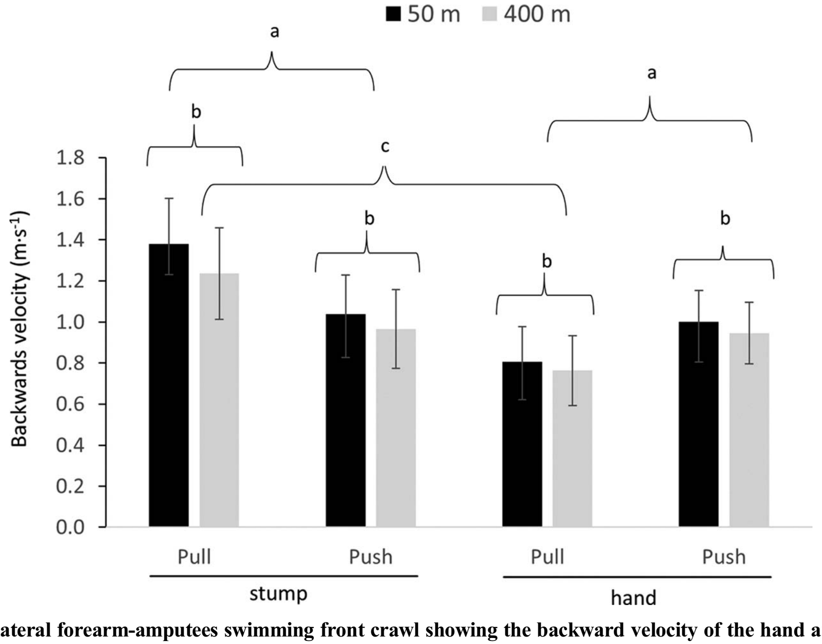

FIGURE 3—Data for 10 unilateral forearm-amputees swimming front crawl showing the backward velocity of the hand and stump, relative to a global reference frame, during their respective pull and push phases at 50-m (*black bars*) and 400-m (*gray bars*) paces (mean ± SD). [a]Significant difference between phases. [b]Significant difference between paces. [c]Significant difference between limb sides.

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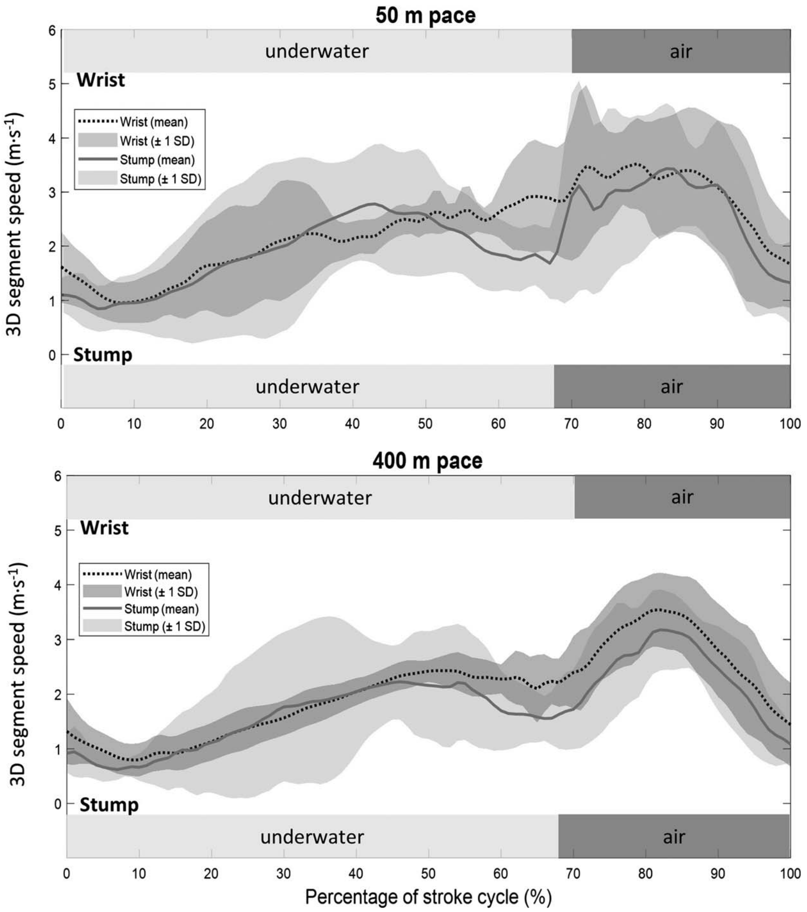

FIGURE 4—Three-dimensional speed of the wrist and the stump, relative to a local reference frame fixed at the swimmer's mass center, during each segment's respective cycle at 50-m and 400-m pace. 0% is water entry for the wrist or the stump, the underwater phase ends when the stump or wrist exits the water, and 100% is the next water entry of the wrist or stump.

(F_9 = 30.85, $P \leq 0.01$, $\eta_p^2 = 0.77$) and limb side (F_9 = 267.59, $P \leq 0.01$, $\eta_p^2 = 0.96$) were found, with no interactions ($P > 0.05$). Resultant segment speed propulsive was lower at the 400-m than 50-m pace and greater for the stump than the wrist ($P \leq 0.001$). Froude efficiency was higher in the 400-m than the 50-m pace ($t_9 = -2.94$, $P < 0.05$, $d = -0.93$). For propulsive Froude efficiency, a main effect of limb side was found, with it greater for the unaffected limb than the residual limb (F_9 = 388.73, $P \leq 0.01$, $\eta_p^2 = 0.98$), with no interaction effects ($P > 0.05$).

Association between swimming velocity, Froude efficiency, intracyclic velocity fluctuation, and upper limb velocity. No significant associations were found between V_{MEAN} and any of the Froude efficiency or intracyclic velocity fluctuation metrics at either swimming pace. Froude efficiency was not associated with any of the intracyclic velocity fluctuation metrics ($P > 0.05$) but had strong negative associations ($r_8 = -0.72$ to -0.88, $P \leq 0.01$) with $V\mathrm{stump}_{\mathrm{UW}}$ and $V\mathrm{wrist}_{\mathrm{UW}}$, at both swimming paces. Strong positive correlations were found between V_{MEAN} and $V\mathrm{stump}_{\mathrm{PROP}}$ (50-m pace: $r_8 = 0.91$, $P < 0.05$; 400-m pace: $r_8 = 0.70$, $P \leq 0.01$) and $V\mathrm{wrist}_{\mathrm{PROP}}$ (50-m pace: $r_8 = 0.81$, $P \leq 0.01$; 400-m pace: $r_8 = 0.68$, $P < 0.05$). Strong associations were also found between $\mathrm{ICVF}_{\%}$ and $\mathrm{ICVF}_{\mathrm{CV}}$ at both 50-m (r_8 = 0.95, $P \leq 0.01$) and 400-m ($r_8 = 0.73$, $P < 0.05$) paces.

DISCUSSION

This study is novel in its analysis of mass center intracyclic velocity fluctuation and Froude efficiency in unilateral forearm-amputee swimmers. The intracyclic velocity fluctuation of these swimmers was within the range of values previously reported in well-trained nondisabled front crawl swimmers. Froude efficiency was lower than values previously reported in nondisabled swimmers, which was particularly evident at the 50-m pace. No intracyclic velocity fluctuation or Froude efficiency variables were associated with swimming performance within the limb amputee cohort.

TABLE 2. Resultant segment speeds and Froude efficiencies for 10 forearm-amputee front crawl swimmers at 50- and 400-m pace (mean ± SD).

		50-m pace	**400-m pace**
Resultant segment speed (m·s^{-1})	$V\mathrm{wrist}_{\mathrm{UW}}$	1.94 ± 0.35	1.71 ± 0.23[b]
	$V\mathrm{stump}_{\mathrm{UW}}$	1.85 ± 0.49[a]	1.53 ± 0.27[a,b]
	$V\mathrm{wrist}_{\mathrm{PROP}}$	2.41 ± 0.24	2.21 ± 0.14[b]
	$V\mathrm{stump}_{\mathrm{PROP}}$	3.42 ± 0.35[a]	3.05 ± 0.25[a,b]
Froude efficiency	Upper limb cycle	0.35 ± 0.05	0.37 ± 0.04[b]
	Unaffected limb	0.54 ± 0.04	0.52 ± 0.03
	Residual limb	0.38 ± 0.02[a]	0.38 ± 0.03[a]

[a] Significant difference and residual limb sides.
[b] Significant difference between paces.

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Intracyclic velocity fluctuation. When swimming at 400-m pace, the forearm amputees had comparable mass center $ICVF_{\%}$ values to those of international level swimmers tested at 200-m pace (23), whereas at 50-m pace, their mean $ICVF_{\%}$ was 18%, lower than the international swimmers'. When considering mass center $ICVF_{CV}$, the amputees produced very similar results to those of well-trained front crawl swimmers (13) but, in contrast, had a 75% lower $ICVF_{CV}$ than another group of international-level swimmers (25). Studies of nondisabled swimmers have found that intracyclic velocity fluctuation remains stable as mean swimming velocity declines during maximum effort front crawl (23,25) and have demonstrated that intracyclic velocity fluctuation is influenced by upper limb coordination (25). Nondisabled swimmers switch from catch-up coordination at slow swimming speeds to opposition or superposition at fast swimming speeds (e.g., [6,7]). In contrast, unilateral forearm amputees do not change upper limb coordination with increases in swimming speed but maintain catch-up coordination, even at maximum speed (45). As catch-up coordination is characterized by a period of no propulsion from the upper limbs, it is surprising that the amputees were able to achieve similar or even lower intracyclic velocity fluctuation than their nondisabled counterparts who could adopt upper limb coordination more conducive to continuous propulsion. This finding may reflect the amputees' ability to minimize hydrodynamic drag more effectively and thus experience less decline in swimming velocity within the cycle. The relative minimum velocities of the amputees provide some indirect evidence to support this notion, as these were 90%–92% of their mean swimming velocity compared with 88.6% for a nondisabled highly trained cohort (23).

There was a clear trend toward a lower intracyclic velocity fluctuation at the 50-m pace than the 400-m pace, with the $ICVF_{CV}$ being significantly lower at the faster pace. Moreover, the shorter upper limb cycle times associated with this faster pace allow less time for the swimmer's velocity to fluctuate. Swimmers also likely used a more rapid, powerful lower limb motion in the 50-m pace trials, compared with their 400-m pace trials, as previous research reported that forearm-amputee swimmers increased their lower limb cycle rate from 1.86 ± 0.31 Hz at 400-m pace to 2.38 ± 0.32 Hz at 50-m pace (46). The lower limbs could thus contribute more to propulsion and help minimize loss of intracyclic velocity more effectively in these faster trials (46).

$ICVF_{\%}$ values in our study are considerably lower than the 35% reported for a homogeneous group of unilateral forearm-amputee swimmers (29), and the $ICVF_{CV}$ values recorded for heterogeneous groups of Para swimmers (24% ± 10%) (22,26,28) as well as for a single female forearm-amputee swimmer (19%–30%) (27). These contrasting values can be explained by differences in the data capture methods used, the test pace and protocol, the performance level of the participants, or the type and severity of the participants' impairment. The mass center $ICVF_{\%}$ values in this study were more than three times the mass center $ICVF_{CV}$ values, indicating that these two measures represent different aspects of intracyclic velocity fluctuation. Because $ICVF_{\%}$ depends only on the maximum and minimum velocity, it is sensitive to extreme values, whereas the $ICVF_{CV}$ provides a more stable measure as it uses the full data set. Although strong associations were found between $ICVF_{CV}$ and $ICVF_{\%}$, only 53% (i.e., $r^2 = 0.53$) of the variance in $ICVF_{CV}$ could be explained by $ICVF_{\%}$ at 400-m pace. Regardless, future investigations of intracyclic velocity fluctuation should present both of these metrics to allow valid comparisons between studies.

Fluctuations in swimmers' mass center velocity occurred continuously throughout an upper limb cycle. In particular, it was apparent that mass center velocity declined soon after the unaffected limb left the water, leaving only the residual limb in the water at ~77% of upper limb cycle for 50-m pace and ~74% for 400-m pace. Conversely, the most sustained increase in mass center velocity occurred during the propulsive phases of the unaffected limb when the stump was out of the water or in its glide phase. Peak mass center velocity coincided with the push phase of the unaffected limb and the glide phase of the residual limb, most likely because of the combined effect of high propulsive forces from the unaffected limb (38) and relatively low drag on the residual limb at this stage in the cycle (9). Conversely, no velocity peak was apparent when the residual limb was in its push phase and the unaffected limb in its glide. This is due to the limited propulsion from the residual limb, coupled with the drag of a full upper limb. These observations confirm that forearm amputees gain swimming speed during their unaffected limb's underwater action and lose speed during their residual limb's underwater action. This finding is consistent with the significant bilateral differences in propulsive force found during unilateral forearm-amputee tethered swimming (10).

The backward velocity of the stump relative to the water in the propulsive phases was greater at 50-m pace than at 400-m pace. This finding substantiates the view that, as swimming speed increases, forearm-amputee swimmers must increase their residual limb velocity if they are to maintain a given level of propulsion (9). Mass center velocity decreased at both paces during the stump's underwater phase, indicating that the stump was producing insufficient propulsion to increase or even maintain mass center velocity (9). Nevertheless, the greater backward velocity of the stump through the water, compared with that of the hand, likely enabled the swimmers to minimize the loss of mass center velocity during this time, thereby limiting intracyclic velocity fluctuation. Although this strategy seems to have benefited the swimmers' intracyclic velocity fluctuation, their Froude efficiency was poorer than that of nondisabled swimmers.

Froude efficiency. This article presents an overall Froude efficiency for a full upper limb cycle, as in all previous studies, but we also present Froude efficiencies for each upper limb independently. Froude efficiency was greater at the slower 400-m pace than at the quicker 50-m pace, indicating that the swimmers were wasting relatively less power in giving kinetic energy to the water at the slower pace (11). At both paces, Froude efficiency was below the range of 0.40–0.47

previously reported for nondisabled highly trained front crawl swimmers (13,34,35), thus demonstrating that this measure may be useful for describing and comparing activity limitation among Para swimmers with limb deficiencies. The specific location and distribution of amputation, for example, a hand amputee versus a below knee amputee, may influence the association between Froude efficiency and performance. Because the hand and forearm provide most of the propulsion in front crawl (8) it would be expected that the absence of these segments would have the greatest impact on Froude efficiency. However, the loss of lower limb segments may also reduce Froude efficiency, as the kicking motion of the lower limbs may directly contribute to propulsion or enhance the propulsive effectiveness of the upper limbs (47). Para swimmers with other impairment types, such as a motor coordination impairment, are also likely to show lower Froude efficiencies than nondisabled counterparts because of their reduced capacity to generate propulsion or to reduce drag (3). For Froude efficiency to be a suitable criterion for classification, it is important to establish those impairment types for which it is a determinant of swimming performance.

The unilateral forearm amputees in this study generally achieved higher Froude efficiencies than found in a mixed group of Para swimmers with a range of impairment types and levels of severity (28). That group included one unilateral forearm-amputee swimmer with a Froude efficiency of 0.40, although direct comparison of this result to our findings is made with caution because they were tested at a pace ~25%–35% slower than we used.

Computation fluid dynamics analysis has previously predicted that with increasing swimming speed, forearm-amputee swimmers must rotate their residual limb faster to produce propulsion effectively (9). We considered that, although this strategy may help compensate for the absent hand and forearm, it could have a negative impact on Froude efficiency. This compromise was evidenced by the strong associations found between limb speed and swimming performance and the strong negative associations found between limb speed and Froude efficiency. When Froude efficiency was calculated for each upper limb independently, it was higher for the unaffected limb than the residual limb. This finding can be explained by the superior surface area of the unaffected limb coupled with its lower velocity during the propulsive phases. The residual limb has only limited capacity for propulsion and may, in fact, be producing a net resistive force during these "propulsive" phases, when the entire upper arm is considered (9). Froude efficiencies of the individual upper limbs in their respective propulsive phases were higher than the overall upper limb cycle Froude efficiency, because of the latter including the nonpropulsive underwater phases of the cycle.

Association between Froude efficiency and intracyclic velocity fluctuation. No previous study has evaluated the association between Froude efficiency and intracyclic velocity fluctuation in Para swimmers. Because both variables have been linked to the energy cost of swimming (11–13) and are influenced by propulsive movements of the upper limbs and mass center velocity profiles, it was speculated that an inverse association would exist between the two. However, the amputee swimmers with the highest Froude efficiencies were not those with the lowest intracyclic velocity fluctuation values, and *vice versa*, indicating that Froude efficiency and intracyclic velocity fluctuation are quite independent measures when obtained from a cohort with the same type and level of impairment. A future study could revisit this premise using a more diverse group of Para swimmers. Neither intracyclic velocity fluctuation nor Froude efficiency was associated with swimming performance in this study, when defined as the swimmer's 50- and 400-m trial pace. This finding was expected given that the participants had the same impairment type and similar training backgrounds and swimming speeds.

An essential stage in the development of new evidence-based classification systems in Para sport is to establish the impact of impairment type and severity on the determinants of performance (5). Our study has demonstrated how a specific limb deficiency impairment affects an established determinant of performance in swimming, namely, Froude efficiency. It seems likely that Para swimmers from other impairment groups, such as those with impaired muscle power or a motor coordination impairment, would also present lower Froude efficiencies than nondisabled swimmers. Further research is required to test this hypothesis and contribute to the limited body of knowledge in this area.

Limitations. This study focuses on a specific impairment type, a unilateral forearm amputation, so our findings are not generalizable to Para swimmers with other limb deficiencies. No control group was used in this study. Instead, existing data on nondisabled swimmers were used to evaluate the impact of forearm amputation on Froude efficiency and intracyclic velocity fluctuation. Care was taken to compare our data only to those from studies where identical computational procedures and well-trained swimmers of similar ages were used. Our study cohort was predominantly female, whereas a majority of previous comparable studies have used male groups. Although there is no evidence that either Froude efficiency or intracyclic velocity fluctuation is influenced by the sex of a swimmer *per se* (11), the anthropometric characteristics of our participants were not matched to those of previous studies. This study included analysis of the underwater velocities of the upper limbs to help explain the intracyclic velocity fluctuations. Our analysis was limited to hand and stump motion in the backward direction only, with the upper limb propulsive phase definitions (pull and push) based on this motion. This approach is appropriate for the motion of the stump, which relies on drag for propulsion (9) but simplifies the more complex motions of the unaffected limb where mediolateral and vertical velocities can also contribute to propulsion (37).

Because of constraints imposed by the camera locations, our analysis was limited to one and a half upper limb cycles. It was assumed that these cycles were representative of each swimmer's normal technique in a nonfatigued state, for the prescribed pace. Future studies could explore fatigue effects and how Para swimmers' Froude efficiency, intracyclic velocity

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fluctuation, and kinematics change throughout a race distance trial, as has done for nondisabled swimmers (23,25). Froude efficiency is the proportion of the external mechanical power produced by the swimmer that is used to overcome hydrodynamic resistance (11). We used a relatively simple mathematical model to represent this complex concept and did not attempt to measure power or hydrodynamic resistance. The model also assumes the effect of lower limb motion is negligible, compared with that of the upper limbs (34).

CONCLUSIONS

Unilateral forearm-amputee swimmers have similar mass center intracyclic velocity fluctuation values to those previously reported in nondisabled well-trained swimmers. As such, intracyclic velocity fluctuation is not a useful criterion for Para swimming classification. Forearm-amputee swimmers are effective at increasing their mass center velocity with their unaffected limb but not with their residual limb, despite rotating their residual limb faster than their unaffected limb. Froude efficiency of forearm amputees is low compared with published values for nondisabled well-trained swimmers, and it is lower for their residual limb than their unaffected limb. As such, Froude efficiency may be a valuable measure of activity limitation in Para swimmers with an upper limb deficiency and a useful metric for comparing swimmers with different types and severity of physical impairment.

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