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Front Crawl Body Roll Characteristics in a Paralympic Medallist and National Level Swimmers with Unilateral Arm Amputation.

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The purpose of this study was to establish the asymmetry and body wave characteristics related to shoulder, hip, knee, and ankle roll in unilateral arm amputee swimmers. Three unilateral arm amputee swimmers, including one Paralympic medallist (swimmer A), volunteered in this study. They conducted two 10-15s front crawl tests with sub-maximum and maximum speeds in a flume. Shoulder, hip, knee, and ankle roll amplitude and progression of a torsional body wave was quantified using a motion capture system and a Fourier analysis. Swimmer A showed 50% higher stroke frequency than the other swimmers. Swimmers achieved larger shoulder roll amplitude toward the affected than the unaffected side by 19 – 89%. Swimmer A showed body wave velocity slowing down when it travelled caudally, while national level swimmers presented increasing wave velocity, suggesting that swimmer A had a less effective kicking than the other swimmers. In conclusion, the technique of the unilateral arm amputee swimmers was characterised by a large shoulder roll angle toward the affected side. The Paralympic medallist had larger shoulder roll asymmetry and less effective kicking than the other swimmers and yet achieved higher swimming speed because of his high stroke frequency.

Keywords: swimming; kinematics; shoulder roll; rhythm; motor control

Introduction

In sports and exercise, adaptations of the training and technical guides are often necessary for physically impaired individuals (DePauw, 1988). Therefore, a good knowledge of skills related to performance is important in disability sports. This is particularly important in swimming since a poor technique reduces swimming performance due to low propulsive forces or the increasing hydrodynamic drag (Zamparo, Gatta, Pendergast, & Capelli, 2009).

In front crawl swimming, which is the fastest swimming technique, primary propulsion (approximately 90 %) is produced by upper limbs (Deschodt, Arsac, &

Rouard, 1999; Gourgoulis et al., 2014). This means that people who do not have adequate arm motion would have difficulty in achieving fast swimming speed. Unilateral arm-amputee swimmers probably need technical skills that differ from those of non-impaired front crawl swimmers since they would have to have a technique which offsets rotational torque around their sagittal axis of the body produced by asymmetric propulsive forces produced by the affected and unaffected limbs. The alternating left and right arm strokes are accompanied by angular motion of the body about its long axis (Psycharakis & Sanders, 2010), which is called body roll and can be divided into the shoulder, hip, knee, and ankle roll (Figure 1). Therefore, it is likely that unilateral arm-amputee swimmers need specific instruction not only for the motion of the upper limbs but also for the body roll technique.

There have been studies that focus on front crawl technique of unilateral arm amputee swimmers. For example, Osborough, Payton, & Daly (2010) reported that unilateral arm amputee swimmers have asymmetric coordination between unaffected and affected limbs. The same authors also provided evidence of kicking patterns varying among this group of swimmers (Osborough, Daly, & Payton, 2015). It has also been reported that maximum shoulder roll amplitude of 45° during the underwater arm motion increases the propulsion produced by the affected limb by 70% compared to the roll amplitude of 0° condition (Lecrivain, Payton, Slaouti, & Kennedy, 2010). This evidence about the relationship between shoulder roll angle and propulsive forces leads to speculation that elite unilateral arm amputee swimmers might show large shoulder roll asymmetry.

Research also indirectly suggests the possibility of shoulder roll asymmetry of unilateral arm amputee swimmers from another perspective. A primary source of the roll of the entire body is the buoyant torque acting on the swimmer (Yanai, 2004).

When a swimmer conducts a recovery motion in front crawl, the centre of buoyancy shifts away from the centre of mass on the plane perpendicular to the longitudinal axis of the swimmer, which generates a rotational effect on the body. The magnitude of the buoyancy depends on the volume of submerged parts of the swimmer’s body. Therefore, it is reasonable to hypothesise that unilateral arm amputee swimmers, who have a lower volume of the upper limb on the affected side, would have an asymmetric roll amplitude of the entire body (larger roll amplitude toward the amputee side than the other side). Given that the entire body roll accounts for 50% of the shoulder roll (Yanai, 2003), it is possible that these swimmers would also have a larger shoulder roll amplitude toward the affected side than the non-affected side.

Figueiredo, Willig, Alves, Vilas-boas, & Fernandes (2014) investigated relationships between biomechanical and physiological variables in a female unilateral front crawl swimmer. They reported that the swimmer increased her energy expenditure per unit of distance (energy cost) as swimming speed increased. However, Morris, Osborne, Shephard, Skinner, & Jenkins (2016) showed no relationship between swimming speed and energy cost in non-impaired female front crawl swimmers. Even though the former study only reported data of one swimmer, these results imply that unilateral arm amputee swimmers are technically ineffective compared with non-impaired swimmers. Indeed, the authors of the former study also reported high intra-cycle velocity variation in the unilateral arm amputee swimmer compared with non-impaired swimmers, which also supported the speculation.

Another difference between unilateral arm amputee swimmers and non-impaired swimmers is the importance of stroke length and frequency. A primary determinant of front crawl performance in non-impaired swimmers is long stroke length (Craig, Skehan, Pawelczyk, & Boomer, 1985; Hellard et al., 2008), while that in unilateral arm amputee is high stroke frequency (Osborough, Payton, & Daly, 2009). Given that high stroke frequency leads to great energy being expended (Barbosa, Fernandes, Keskinen, & Vilas-Boas, 2008; Zamparo, Pendergast, Mollendorf, Termin, & Minetti, 2005), it is possible that unilateral arm amputee swimmers sacrifice efficiency to a greater extent than non-impaired swimmers when achieving high swimming speed.

A potential explanation that links the biomechanical and energetic characteristics in unilateral arm amputee swimmers is a rolling rhythm. Sanders & Psycharakis (2009) investigated a body roll rhythm by dividing the shoulder, hip, knee, and ankle roll angle into three waves (Figure 2). The waves are the fundamental frequency with one maxima/minima (due mostly to the rolling motion of the upper body, H1), the second harmonic with two maxima/minima (produced by the hydrodynamic torque produced by continuous upward and downward stroke motion of the upper limbs, H2), and the third harmonic with three maxima/minima (caused by hydrodynamic torque produced by three alternate kicking actions of the legs – six-beat kicking pattern, H3).

Figure 1 near here

Figure 2 near here

They reported that skilled competitive swimmers were characterised by H3 wave travelling from hip to ankles with modest and increasing velocity. From the results, they suggested that those swimmers conducted their leg kicking during front crawl swimming with a more effective manner than less skilled swimmers from a hydrodynamic perspective. This suggestion was based on evidence that efficient propulsion from caudal transmission of body waves in marine animals is characterised by wave velocities relative to the body that are slightly faster than their forward motion with a tendency to increase as it travels caudally, which shows high propulsive efficiency (Sfakiotakis, Lane, & Davies, 1999). Sanders & Psycharakis also observed H1 contribution remaining strong in knee and ankle roll, suggesting that the wave originating in the upper body influenced the rhythm and range of the motion of the lower limbs.

Given that unilateral arm amputee swimmers have a variety of kicking patterns (Osborough, Daly, & Payton, 2015) and there is a possibility of the asymmetric rolling motion of the shoulder and/or the entire body (Lecrivain et al., 2010; Yanai, 2003, 2004), it is possible that unilateral arm amputee swimmers have rolling rhythms that differ from that in non-impaired swimmers. In the light of evidence suggesting the possibility of the energy cost difference between unilateral arm amputee and non-impaired swimmers, unilateral arm amputee swimmers might show ineffective manners of rolling rhythm (such as too fast body wave velocity). Considering the evidence of stroke frequency being important in unilateral arm amputee swimmers (Osborough et al., 2009), it is likely that this group of swimmers would show fast body wave velocities because high stroke frequency requires swimmers to transfer the body wave quickly at a given swimming speed.

In the light of the links between the rolling kinematics and physiological/biomechanical aspects in front crawl, understanding the kinematic characteristics in unilateral arm amputee swimmers and their differences from those in non-impaired swimmers would be useful as fundamental knowledge of front crawl technique in swimmers with the amputation. Therefore, the purpose of the present study was to establish the body roll asymmetry and wave characteristics (phase angle and velocity) related to body roll between shoulder-hip, hip-knee, and knee-ankle in unilateral arm amputee swimmers. We hypothesised that shoulder roll amplitude of unilateral arm amputee swimmers is larger toward the affected side than the unaffected side, and unilateral amputee swimmers would show fast caudal wave velocity (much faster than the forward swimming speed) between shoulder-hip, hip-knee, and knee-ankle roll.

Methods

Participants

Three unilateral arm amputee swimmers (Table 1) participated in the present study. All participants had a unilateral amputation at elbow level. Swimmer A had won a medal in a front crawl event of Paralympic Games, and the other two had experiences in competing at front crawl finals of national Para-swimming competitions. All athletes were competing at official competitions in S9 class, which is categorised as the second most functional group among physical impairment classes in front crawl, backstroke, and butterfly events (Daly & Vanlandewijck, 1999; International Paralympic Committee, 2018). At the time of the testing, the sport class status of swimmer A, B, and C was ‘C (the classification status had been internationally confirmed)’, ‘J (the classification status had been nationally confirmed)’, and ‘R2020 (the classification status had been internationally approved with a condition of future status review in 2020)’, respectively. The ethics committee of the university approved the purpose, procedure, and potential risks of the present study. Swimmer A and Swimmer B provided their written informed consent by themselves. For Swimmer C, both the swimmer and her parent gave the consent for the participation.

Table 1 near here

Procedures

The testing session was conducted in an indoor water flume (Igarashi Industrial Works Co. Ltd., Japan), which was designed to control the water flow velocity from 0.0 to 2.5 m/s. With this system, each swimmer was required to swim against the water flow so that the swimmer could maintain his/her position in the flume while achieving comparable exercise intensity and motion as the swimmer does when swimming with the corresponding swimming speed in the pool. The participants conducted their individual warm up before the testing in an indoor pool and the flume, which included familiarisation of the testing environment.

The swimmers were marked on their Styloid Process of Ulna (wrist), Lateral Epicondyle of Humerus (elbow), Acromion Process (shoulder), Greater Trochanter (Hip), Lateral Epicondyle of Femur (knee), and Lateral Malleolus (ankle) for each side of the body using active light-emitting diode (LED) markers, and a motion capture system was used to analyse the motion of the swimmers (VENUS3D, Nobby Tech. Ltd., Tokyo, Japan). A total of 24 motion capture cameras (four for the above water and 20 for the underwater area) were positioned around the flume, and the area the swimmers were required to perform in the flume was calibrated to obtain three-dimensional (3D) object space coordinates using a Direct Linear Transformation method before the testing. A dynamic calibration method was used for the calibration process, and mean reconstruction errors were 0.5 and 0.8 mm for above and under the water surface area, respectively. The reconstruction error represents the mean difference between the location of the centre of wand markers detected by each camera, which was obtained using reconstructed coordinates and each camera coordinate (residual error). The definition of the 3D coordinates was X-direction (swimming direction), Y-direction (vertical direction) and Z-direction (the direction perpendicular to X- and Y-directions).

The approximate volume was 3.75 m^2 (2.5 m in the X-direction, 1.0 m in the Y-direction, and 1.5-m in the Z direction) for both above and underwater calibrated space (a total volume of 7.5 m^2).

The swimmers performed two 10-15 s swim trials in the flume with their sub-maximum and maximum effort. The flow velocity of the maximum effort trial was determined a day before the testing using the same flume, and the sub-maximum speed was 90% flow velocity of that in the maximum trial. This was based on the rationale that 90% of maximum swimming velocity corresponding to approximate 200 m race velocity (Seifert, Boulesteix, & Chollet, 2004; Seifert, Chollet, & Bardy, 2004), which is comparable to a previous study that used a Fourier analysis for a body roll investigation (Sanders & Psycharakis, 2009). The flow velocities of sub-maximum and maximum trials were 1.63 and 1.80 m/s for swimmer A, 1.30 and 1.43 m/s for swimmer B, and 1.25 and 1.35 for swimmer C, respectively.

Data processing and analysis

The obtained coordinate raw data were treated in VENUS3D software. Using the software, error data due to the LED light reflection at the water surface were excluded, and the coordinate data of each joint of the swimmers were smoothed using a Butterworth low-pass filter with a cut-off frequency of 6 Hz. Seven complete stroke cycles (defined as the duration between the entry of the right wrist to the water and the subsequent entry of the same wrist), which did not contain the breathing motion (that was checked by a video camera synchronised with the motion capture system), were analysed.

The number of the stroke cycles achieved in one second (Stroke frequency; Hz) was obtained by the inverse of each stroke cycle time. The roll angle of each joint pair (shoulder, hip, knee, and ankle) was determined by projecting the joint vector of the respective right relative to the left joint onto the plane perpendicular to the swimming direction (arctangent of the ratio of Z- and Y-vector coordinates). Maximum roll angles toward both affected and unaffected directions of each joint were identified by obtaining the absolute value of the maximum and minimum of each roll angle time series during each stroke cycle.

Fourier analysis was used in accordance with Sanders & Psycharakis (2009) to investigate the rhythm of the body roll. In their study, it was assumed that the rolling action of the whole body contained three frequencies described in the introduction; H1, H2, and H3. In the present study, the same assumption was made for Swimmer C, who had a six-beat kicking pattern. However, Swimmer A and Swimmer C had a four-beat kicking pattern (two alternate kicking actions instead of three during a stroke cycle). Therefore, for those two swimmers, it was assumed that the rolling motion of the participant at this trial contained only H1 and H2 frequencies.

The roll angle data on each joint vector was input to a Fourier analysis using MATLAB (MathWorks, Natick, Massachusetts, United States) to obtain the cosine and sine coefficients (A_n and B_n for the *n*th Fourier frequency, respectively) of the fundamental waves. The purpose of the Fourier analysis was to transform signals into a given number of frequencies, rather than to detect all frequencies included in the original signals. Therefore, A_n and B_n were obtained from curves that have the best fit to the original signals from each stroke cycle under the assumption that each roll angle signal was composed predominantly of two or three frequency harmonics. The best-fit curves were expressed by

$$y = A_0 + \sum_{n=1}^{2 or 3} A_n \cos(nwx) + B_n \sin(nwx)$$

where A_0 models a constant term in the data, *w* is the fundamental frequency of the signal, and *n* is the number of harmonics in the series. The amplitude of *n*th frequency, contribution by each frequency to the mean square value of the average power of the signal, phase angle and wave velocity of each frequency between shoulder-hip, hip-knee, and knee-ankle were all calculated by the manner described in Sanders & Psycharakis (2009).

Statistical analysis

The intraclass correlation (ICC) was calculated for all trials based on absolute-agreement and two-way mixed-effects model to check the level of absolute agreement between the best-fit curves and the original signals. In this study, means and standard deviations of all variables were calculated. Cohen's d was calculated when comparing variables between individuals or between the two trials. Based on Cohen's (1992) suggestion, it was defined that effect sizes of 0.2 are small, 0.5 are moderate, and 0.8 are large. ICC was obtained using IBM SPSS Statistics 24 (IBM Corporation, Somers, NY, USA), and Cohen's d was calculated by Microsoft Office Excel 2013.

Results

ICC calculated for all participants and trials showed excellent agreement between the original curves and the best-fit models for all roll (Koo & Li, 2016). Among all trials and stroke cycles, the smallest ICC observed was 0.998, 0.989, 0.970, and 0.962 for shoulder, hip, knee, and ankle roll, respectively. All ICC coefficients calculated in the present study were significant with $p < 0.001$

Figure 3 presents the stroke frequency of the swimmers. Swimmer A showed the highest stroke frequency followed by swimmer B and swimmer C. Swimmer A, B, and C increased their stroke frequency by 6.4, 10.1, and 3.6% (d=3.86, 3.26, and 1.65) from the sub-maximum speed trial to the maximum speed trial, respectively. Figure 4 shows the maximum roll amplitude of each joint toward both the affected and unaffected side. Swimmers rolled their shoulder toward the affected side more than toward the unaffected side (d=24.58, 3.50, and 1.57 at the sub-maximum trial, and d=23.63, 2.91, and 0.90 at the maximum trial for swimmer A, B, and C, respectively), while they did not show a common tendency in other roll amplitudes.

Figure 3 near here

Figure 4 near here

Table 2 and 3 display the contribution of each harmonic to the shoulder, hip, knee, and ankle rolls at the sub-maximum and maximum trials, respectively. H1 contributed to the shoulder and hip roll the most in all three swimmers. H2 had the largest contribution to the knee and ankle rolls in swimmer A and B, whereas H3 contributed the most to the knee and ankle rolls in swimmer C at both trials. The contribution of H1 to the ankle roll amplitude was small (less than 4%) in all swimmers at both trials.

Table 2 near here

Table 3 near here

Table 4 and Table 5 exhibit the phase angle of a dominant harmonic between shoulder-hip, hip- knee, and knee- ankle and wave velocity travelling through these joint pairs, respectively. All swimmers tended to roll their hip before the shoulder, knee, and ankle. Swimmer A showed H2 velocity slowing down when it travelled from the hip to the ankle. On the other hand, swimmer B and C presented increasing H2 (swimmer B) and H3 (swimmer C) wave velocity as it travelled caudally.

Table 4 near here

Table 5 near here

Discussion and Implications

In the present study, best-fit equation models were used for the Fourier analysis rather than analysing the original signal. The absolute agreement between the original segment roll signals and the models were very high (ICC > 0.95). This result showed that the modelled signal accurately represented the original segment roll signals, and the assumption of the body roll angle signal consisting of a small number of frequencies (two or three, depending on the kick pattern) was vindicated.

As initially hypothesised, all three swimmers rolled their shoulder more toward the affected side than the other side. This was not the case for the hip, knee and ankle roll angles, i.e., each swimmer had an individual tendency. The shoulder roll asymmetry was particularly notable in swimmer A, who is the fastest swimmer among the three. Lee, Sanders, & Payton, (2014) reported a strong relationship between the maximum force when fully tethered and 100 m front crawl performance. Therefore, it is likely that swimmer A produced larger propulsive forces than the other two swimmers. Perhaps the large shoulder roll angle toward the affected side in swimmer A contributed to produce high propulsive forces using the affected limb, as suggested by Lecrivain et al. (2010) who reported that maximum shoulder roll amplitude of 45° during the underwater arm motion increases the propulsion produced by the affected limb than 0° shoulder roll condition.

The higher stroke frequency in swimmer A compared to swimmer B and C also supports this possibility. Swimmer A achieved approximately 50% higher stroke frequency than the other two swimmers, even though the differences in the flow velocity between them were about 25-30%. Lecrivain et al. (2010) reported that at a given swimming speed, 20% acceleration or deceleration of the arm angular velocity would have a major impact on propulsive forces produced by the affected arm (maximum propulsive force being double or half). If this is the case, it is possible that swimmer A relied on his affected arm to produce large propulsion more than the other swimmers.

Even though the propulsion produced by the affected limb would not be large, maximising it should be very important for unilateral arm amputee swimmers. It has been reported that a unilateral arm amputee swimmer increased the energy cost while increasing the swimming speed (Figueiredo et al., 2014). On the other hand, non-impaired swimmers show a stable energy cost regardless of the swimming speed (Morris et al., 2016). Maximising the propulsion by the affected arm would contribute to minimising the intra-cycle velocity fluctuation, which would contribute to reducing the energy cost of the swimmer. Nevertheless, the current study did not quantify any kinetic variables. Therefore, further investigation would be necessary to establish detailed relationships between the stroke frequency, propulsive force, and swimming performance in this group of swimmers.

We also hypothesised that the unilateral arm amputee swimmers would show fast wave velocity toward the caudal direction between shoulder-hip, hip-knee, and knee-ankle roll, under the assumption of unilateral arm amputee swimmers being technically less effective than non-impaired swimmers. We focused on a dominant frequency in each segment to quantify the wave velocity. The dominant frequency was H1 in shoulder and hip roll, and H2 (swimmer A and B) and H3 (swimmer C) in knee and ankle roll.

Sanders & Psycharakis (2009) showed H3 velocity travelling caudally with approximately 2.5 and 3.0 times (for hip-knee and knee-ankle, respectively) faster than the forward swimming speed in non-impaired swimmers. Interestingly, the swimmers in this study showed 0.8-1.5 and 1.3-2.0 times faster hip-knee and knee-ankle wave velocity than the flow velocity, which was much smaller than the value in the study of Sanders & Psycharakis. Sanders & Psycharakis did not report shoulder-hip wave velocity of a dominant frequency (H1). However, given that shoulder-hip H1 phase difference ranged from -9.9 to -3.8 degrees in non-impaired swimmers (reported in Sanders & Psycharakis), it is probable that H1 velocity between shoulder-hip in the current study’s participants was much smaller because they show larger differences in shoulder-hip phase angle (ranged from -51 to -28 degrees). Therefore, the second hypothesis was not supported.

Wave velocity analysis also demonstrated that H2 wave velocity slowed down as it travelled in the cephalo-caudal direction in swimmer A. This has been recognised as an ineffective kicking pattern often presented by unskilled swimming motion (Sanders, 2007). On the other hand, Swimmer B and C presented a wave velocity due to the kicking motion (H2 and H3, respectively) travelling from hip to ankle with an increasing velocity slightly faster than the flow velocity. Given that the body wave velocity should be closer to, and yet slightly faster than, the swimming speed (Sanders, 2007; Sanders, Cappaert, & Devlin, 1995; Sanders & Psycharakis, 2009), it is surprising to observe the ineffective manner only in the elite swimmer who has won a medal in a Paralympic Games.

Swimmer A might have sacrificed the propulsive efficiency in leg kicking to achieve high stroke frequency. Swimmer A achieved higher stroke frequency than Swimmer B and C by more than 30%. If Swimmer A had a 50% slower wave velocity (similar wave velocity as Swimmer C), the swimmer should spend twice more time in moving H2 wave between hip and knee, which would cause approximately 0.2 s additional stroke cycle time because the phase angle between hip and knee H2 for Swimmer A was approximately 70˚ with stroke cycle time of 0.81 - 0.86 s. This would decrease his stroke frequency by 20%. It has been reported that a major factor of determining front crawl performance in unilateral arm amputee swimmers is high stroke frequency (Osborough, Payton, & Daly, 2009), unlike non-impaired swimmers whose performance determinant is primarily a long stroke length (Craig, Skehan, Pawelczyk, & Boomer, 1985; Hellard et al., 2008). Therefore, it is reasonable to speculate that swimmer A is faster than swimmer B and C because he has an advantage over the other two swimmers in high stroke frequency, even though he had less effective wave velocity pattern than the other two swimmers.

On the other hand, the slow and increasing wave velocity in swimmer B and C might imply that they rely on their leg kick more than swimmer A and non-impaired swimmers. Fulton, Pyne, & Burkett (2011) reported that the towing force in a group of Paralympic simmers with streamlining was approximately 20 N larger than that with kicking, showing the propulsive effect of the kick. Fulton et al. also speculated that upper limb impairments strongly depend on the kicking action. Perhaps the swimmer B and C in the current study adapted their kick technique to maximise the propulsion produced by the lower limbs. It should be noted that the present study did not include any kinetic analysis, and the study by Fulton et al. included not only swimmers with upper limb impairment but a wide variety of Paralympic swimmers. Therefore, the contribution of the kick to swimming performance in unilateral arm amputee swimmers and its difference from non-impaired swimmers should be further investigated. It would also be of interest to quantify to what extent stroke frequency and the leg kick contribute to swimming performance depending on the swimming speed (i.e. race distance).

At both trials, swimmer A and B had the largest contribution of H1 in shoulder and hip roll, and H2 in knee and ankle roll and swimmer C had the largest contribution of H3 in her knee and ankle roll instead of H2. Since ankle and knee rolls are affected hugely by the kicking rhythm, it is understandable that swimmer A and B (who had a four-beat kicking pattern) and swimmer C (who had a six-beat kicking rhythm) had different wave components and contribution. Sanders & Psycharakis (2009) reported a strong (if not dominant) contribution of H1 to knee and ankle roll during 200 m front crawl swimming in non-impaired swimmers. In their study, the contribution of H1 to knee and ankle roll was approximately 18-26 and 6-13%, respectively. In knee and ankle rolls, swimmer C showed approximately 22 and 10% (sub-maximum) and 26 and 7% (maximum) of H1 contribution, respectively, which was comparable with the results reported in Sanders & Psycharakis. On the other hand, the other two swimmers had much smaller H1 contribution to knee and ankle rolls (less than 10 and 3%, respectively).

These results imply that swimmer A and B had less-coordinated upper and lower limbs combination. The speculation of the poor coordination for those two swimmers is also clear from the fact that the swimmers conducted continuous four-beat kicking. From a perspective of body roll, a swimmer should conduct an odd number (either one or three times) of kicking in one arm stroke; otherwise, the trunk twist (due to the kick motion and shoulder roll) would be completely different between left and right arm strokes. For example, if a swimmer conduct a left leg kick when entering his/her right arm, the swimmer subsequently do a right leg kick, and the swimmer would conduct a left leg kick again when his/her left arm enters the water (i.e., the trunk would be twisted during right arm entry, but not during the left). For those swimmers, perhaps four-beat kicking pattern was to produce larger shoulder angle toward the affected side. In shoulder roll angle, both swimmers had a peak of H2 wave toward the affected side almost at the same timing as H1 showed its peak toward the same side. Assuming that this H2 wave originated from the four-beat kicking motion (i.e. two peaks roll motion), it is possible that the four-beat kicking assisted the shoulder roll toward the affected side (Appendix I and II).

These results imply that unilateral arm amputee swimmers might have to sacrifice effective motion patterns (such as upper and lower limbs coordination and lower limbs motion using a caudal body wave transfer) to achieve high stroke frequency (and consequently large swimming velocity). Another implication from the present study is that unilateral arm amputee swimmers with a high stroke frequency might have larger asymmetry and energetically less efficient technique than other swimmers, which should be in consideration when coaches prescribe training to unilateral arm amputee swimmers.

Conclusion

Unilateral arm amputee swimmers were characterised by larger shoulder roll toward the affected side than the unaffected side, which was particularly notable in the best swimmer. The body wave velocity from hips to ankles indicated that the kicking rhythm of a Paralympic medallist swimmer was less effective than national level swimmers. On the other hand, the best swimmer achieved the highest stroke frequency among the three swimmers tested. National level unilateral arm amputee swimmers had an effective manner of body wave velocity.

Disclosure statement

The authors declare no conflicts of interest.

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References

Barbosa, T., Fernandes, R. J., Keskinen, K. L., & Vilas-Boas, J. P. (2008). The influence of stroke mechanics into energy cost of elite swimmers. *European Journal of Applied Physiology*, *103*(2), 139–149. doi:10.1007/s00421-008-0676-z

Cohen, J. (1992). A Power Primer. *Psychological Bulletin, 112*, 155–159.

Craig, A. B., Skehan, P. L., Pawelczyk, J. . A., & Boomer, W. L. (1985). Velocity, stroke rate, and distance per stroke during elite swimming competition. *Medicine* *and Science in Sports and Exercise*, *17*(6), 625–634. doi:10.1249/00005768-198512000-00001

Daly, D. J., & Vanlandewijck, Y. (1999). Some criteria for evaluating the “fairness” of swimming classification. *Adapted Physical Activity Quarterly*, 16, 271–289. doi:10.1123/apaq.16.3.271

DePauw, K. P. (1988). Sport for individuals with disabilities: Research opportunities. *Adapted Physical Activity Quarterly*, *5*(2), 80–89. doi:10.1123/apaq.5.2.80

Deschodt, J. V., Arsac, L. M., & Rouard, A. H. (1999). Relative contribution of arms and legs in humans to propulsion in 25-m sprint front-crawl swimming. *European Journal of Applied Physiology*, *80*(3), 192–199. doi:10.1007/s004210050581

Figueiredo, P., Willig, R., Alves, F., Vilas-boas, J. P., & Fernandes, R. J. (2014). Biophysical characterization of a unilateral arm amputee swimmer : A case study. *International Journal of Sports Physiology and Performance*, *9*, 1050–1053. doi:10.1123/ijspp.2013-0438

Fulton, S. K., Pyne, D., & Burkett, B. (2011). Optimizing kick rate and amplitude for Paralympic swimmers via net force measures. *Journal of Sports Sciences*, *29*(4), 381–387. doi:10.1080/02640414.2010.536247

Gourgoulis, V., Boli, A., Aggeloussis, N., Toubekis, A., Antoniou, P., Kasimatis, P., … Mavromatis, G. (2014). The effect of leg kick on sprint front crawl swimming. *Journal of Sports Sciences*, *32*(3), 278–289. doi:10.1080/02640414.2013.823224

Hellard, P., Dekerle, J., Avalos, M., Caudal, N., Knopp, M., & Hausswirth, C. (2008). Kinematic measures and stroke rate variability in elite female 200-m swimmers in the four swimming techniques: Athens 2004 Olympic semi-finalists and French National 2004 Championship semi-finalists. *Journal of Sports Sciences*, *26*(1), 35–

46. doi:10.1080/02640410701332515

International Paralympic Committee. (2018). World Para swimming classification rules and regulations. Retrieved from www.paralympic.org/sites/default/files/document/180122090541633_2018_1_18_WPS%2BRules%2Band%2BRegulations%2B2018-2021_Final2-%2Bfor%2Bwebsite.pdf

Koo, T. K., & Li, M. Y. (2016). A Guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine, 15*(2), 155–163. doi:10.1016/j.jcm.2016.02.012

Lecrivain, G., Payton, C., Slaouti, A., & Kennedy, I. (2010). Effect of body roll amplitude and arm rotation speed on propulsion of arm amputee swimmers. *Journal of Biomechanics, 43*(6), 1111–1117. doi:10.1016/j.jbiomech.2009.12.014

Lee, C. J. an., Sanders, R. H., & Payton, C. J. (2014). Changes in force production and stroke parameters of trained able-bodied and unilateral arm-amputee female swimmers during a 30 s tethered front-crawl swim. *Journal of Sports Sciences, 32*(18), 1704–1711. doi:10.1080/02640414.2014.915420

Morris, K. S., Osborne, M. A., Shephard, M. E., Skinner, T. L., & Jenkins, D. G. (2016). Velocity , aerobic power and metabolic cost of whole body and arms only front crawl swimming at various stroke rates. *European Journal of Applied Physiology, 116*(5), 1075–1085. doi:10.1007/s00421-016-3372-4

Osborough, C. D., Daly, D., & Payton, C. (2015). Effect of swim speed on leg-to-arm coordination in unilateral arm amputee front crawl swimmers. *Journal of Sports Sciences, 33*(14), 1523–1531. doi:10.1080/02640414.2014.996181

Osborough, C. D., Payton, C., & Daly, D. J. (2010). Influence of swimming speed on inter-arm coordination in competitive unilateral arm amputee front crawl swimmers. *Human Movement Science*, *29*(6), 921–931. doi:10.1016/j.humov.2010.05.009

Osborough, C. D., Payton, C. J., & Daly, D. J. (2009). Relationships between the front crawl stroke parameters of competitive unilateral arm amputee swimmers, with selected anthropometric characteristics. *Journal of Applied Biomechanics*, *25*(4), 304–312. doi:10.1123/jab.25.4.304

Psycharakis, S. G., & Sanders, R. (2010). Body roll in swimming: a review. *Journal of Sports Sciences*, *28*(3), 229–236. doi:10.1080/02640410903508847

Sanders, R. (2007). Kinematics, coordination, variability, and biological noise in the prone flutter kick at different levels of a “learn-to-swim” programme. *Journal of Sports Sciences*, *25*(2), 213–227. doi:10.1080/02640410600631025

Sanders, R., Cappaert, J. M., & Devlin, R. K. (1995). Wave characteristics of butterfly swimming. *Journal of Biomechanics*, *28*(1), 9–16. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/7852446

Sanders, R., & Psycharakis, S. G. (2009). Rolling rhythms in front crawl swimming with six-beat kick. *Journal of Biomechanics*, *42*(3), 273–279. doi:10.1016/j.jbiomech.2008.10.037

Seifert, L., Boulesteix, L., & Chollet, D. (2004). Effect of gender on the adaptation of arm coordination in front crawl. *International Journal of Sports Medicine*, *25*(3), 217–223. doi:10.1055/s-2003-45253

Seifert, L., Chollet, D., & Bardy, B. G. (2004). Effect of swimming velocity on arm coordination in the front crawl: a dynamic analysis. *Journal of Sports Sciences*, *22*(7), 651–660. doi:10.1080/02640410310001655787

Sfakiotakis, M., Lane, D. M., & Davies, J. B. C. (1999). Review of fish swimming modes for aquatic locomotion. *IEEE Journal of Oceanic Engineering*, *24*(2), 237–252. doi:10.1109/48.757275

Yanai, T. (2003). Stroke frequency in front crawl: its mechanical link to the fluid forces required in non-propulsive directions. *Journal of Biomechanics*, *36*(1), 53–62. doi:10.1016/S0021-9290(02)00299-3

Yanai, T. (2004). Buoyancy is the primary source of generating bodyroll in front-crawl swimming. *Journal of Biomechanics*, *37*(5), 605–612. doi:10.1016/j.jbiomech.2003.10.004

Zamparo, P., Gatta, G., Pendergast, D., & Capelli, C. (2009). Active and passive drag: The role of trunk incline. *European Journal of Applied Physiology*, *106*(2), 195–205. doi:10.1007/s00421-009-1007-8

Zamparo, P., Pendergast, D. R., Mollendorf, J., Termin, A., & Minetti, A. E. (2005). An energy balance of front crawl. *European Journal of Applied Physiology*, *94*, 134–144. doi:10.1007/s00421-004-1281-4

Table 1. Age, gender, and anthropometric characteristics of the participants.

Swimmer	Gender	Age (years)	Height (m)	Mass (kg)	Amputee side
A	Male	25.0	176.0	72.5	Left
B	Male	25.0	169.0	62.0	Left
C	Female	15.0	159.0	54.0	Right

Table 2. Contribution of each harmonic to shoulder, hip, knee, and ankle rolls at the sub-maximum trial.

Swimmer	Wave	Roll			
		Shoulder	Hip	Knee	Ankle
A	H1	93.73±0.56	84.88±7.61	8.99±4.69	1.66±0.91
	H2	3.90±0.32	10.94±2.56	84.21±7.60	97.83±1.26
B	H1	96.53±0.93	85.10±5.91	8.49±3.71	n/a
	H2	3.10±0.72	11.49±4.01	70.08±11.16	97.34±2.54
C	H1	91.43±2.78	81.77±7.12	19.18±7.91	1.44±1.86
	H2	1.46±0.80	1.01±0.82	7.60±5.06	10.04±3.32
	H3	2.09±0.55	7.30±2.29	55.21±11.23	86.76±4.94

Table 3. Contribution of each harmonic to shoulder, hip, knee, and ankle rolls at the maximum trial.

Swimmer	Wave	Roll			
		Shoulder	Hip	Knee	Ankle
A	H1	91.18±1.16	78.01±4.62	4.28±1.98	2.76±2.18
	H2	3.85±0.21	11.55±2.39	92.62±2.83	96.53±2.87
B	H1	93.69±2.95	72.97±13.01	4.74±1.95	1.23±1.02
	H2	4.31±1.87	15.57±8.11	73.68±4.23	96.87±1.77
C	H1	93.78±4.94	84.18±5.99	23.43±13.11	3.56±3.27
	H2	1.12±0.54	2.68±2.71	4.61±2.32	6.16±6.27
	H3	1.30±0.57	9.98±6.08	58.03±15.49	85.30±18.28

Table 4. Phase difference (°) of dominant harmonics (H1 for shoulder-hip, H2 for hip-knee and knee-ankle in Swimmer A and B, and H3 for hip-knee and knee-ankle in Swimmer C) between shoulder–hip, hip–knee, and knee–ankle (Mean±SD among the seven trials).

Trial	**Swimmer**	**Shoulder-Hip (H1)**	**Hip-Knee (H2 or H3)**	**Knee-Ankle (H2 or H3)**
Sub-maximum	**A**	-51.04±2.04	71.30±6.94	75.54±8.36
	B	-28.20±4.24	80.48±16.50	36.47±3.60
	C	-28.20±5.91	111.97±30.59	69.11±32.93
Maximum	**A**	-51.20±1.70	72.11±12.53	70.45±6.63
	B	-36.08±8.97	74.36±21.36	49.06±18.23
	C	-31.72±9.40	88.20±11.63	77.43±29.47

Table 5. Wave velocity (m/s) of dominant harmonics (H1 for shoulder-hip, H2 for hip-knee and knee-ankle in Swimmer A and B, and H3 for hip-knee and knee-ankle in Swimmer C) between shoulder–hip, hip–knee, and knee–ankle (Mean±SD among the seven trials)

Trial	**Swimmer**	**Shoulder-Hip (H1)**	**Hip-Knee (H2 or H3)**	**Knee-Ankle (H2 or H3)**
Sub-maximum	A	-4.98±0.16	2.37±0.26	2.19±0.23
	B	-5.50±0.76	1.50±0.44	2.58±0.25
	C	-5.14±0.89	1.05±0.22	1.74±1.26
Maximum	A	51.20±1.70	-72.11±12.53	-70.45±6.63
	B	36.08±8.97	-74.36±21.36	-49.06±18.23
	C	31.72±9.40	-88.20±11.63	-77.43±29.47

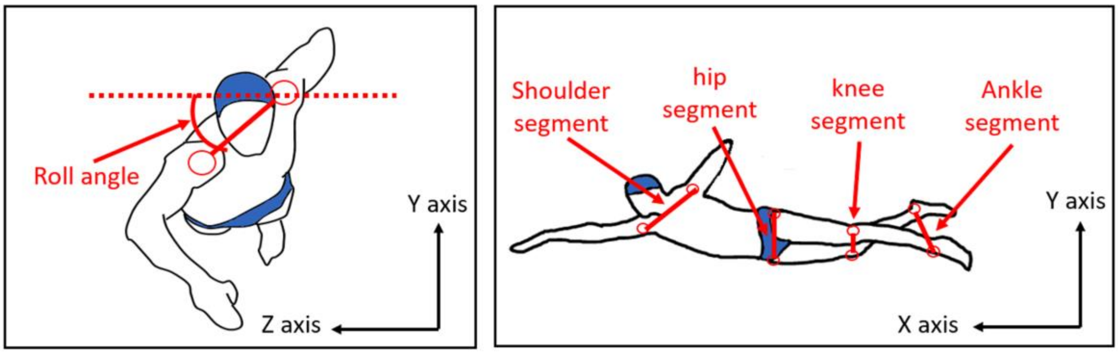
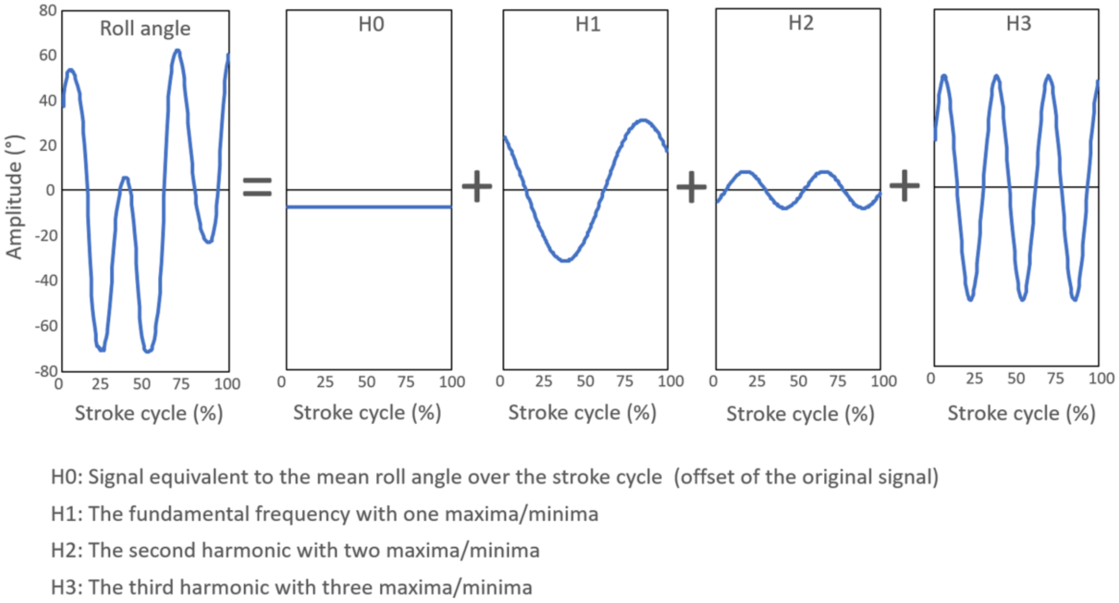


Figure 1. Definitions of the roll angle and each segment.



H0: Signal equivalent to the mean roll angle over the stroke cycle (offset of the original signal)

H1: The fundamental frequency with one maxima/minima

H2: The second harmonic with two maxima/minima

H3: The third harmonic with three maxima/minima

Figure 2. Fourier analysis for the roll angle (Ankle roll signal is displayed as an example).

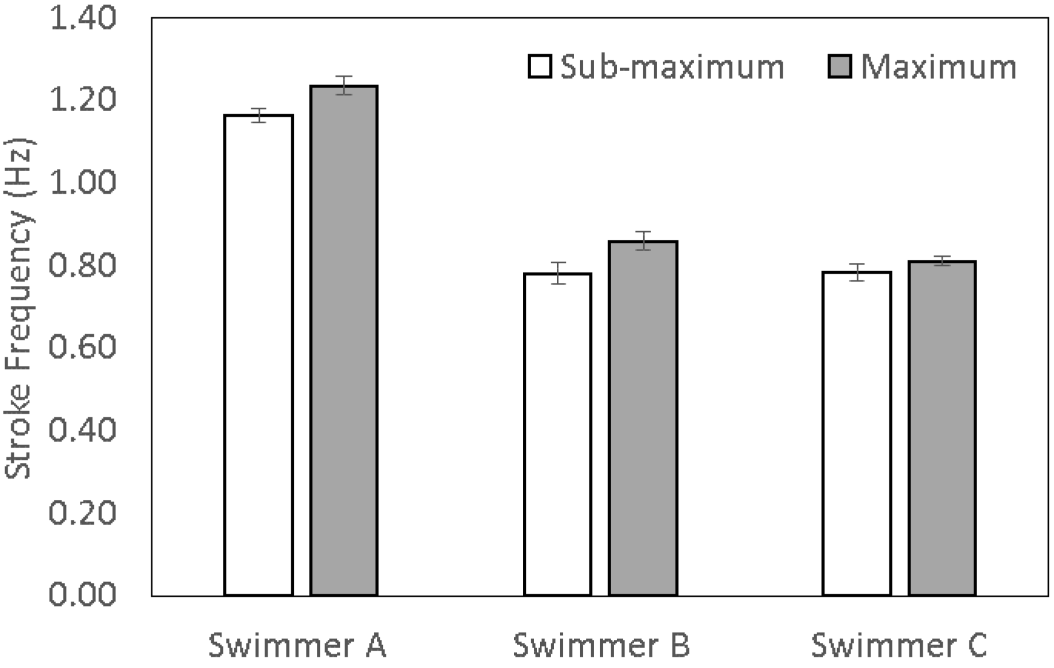


Figure 3. Stroke frequency of the swimmers at the sub-maximum and maximum trials.

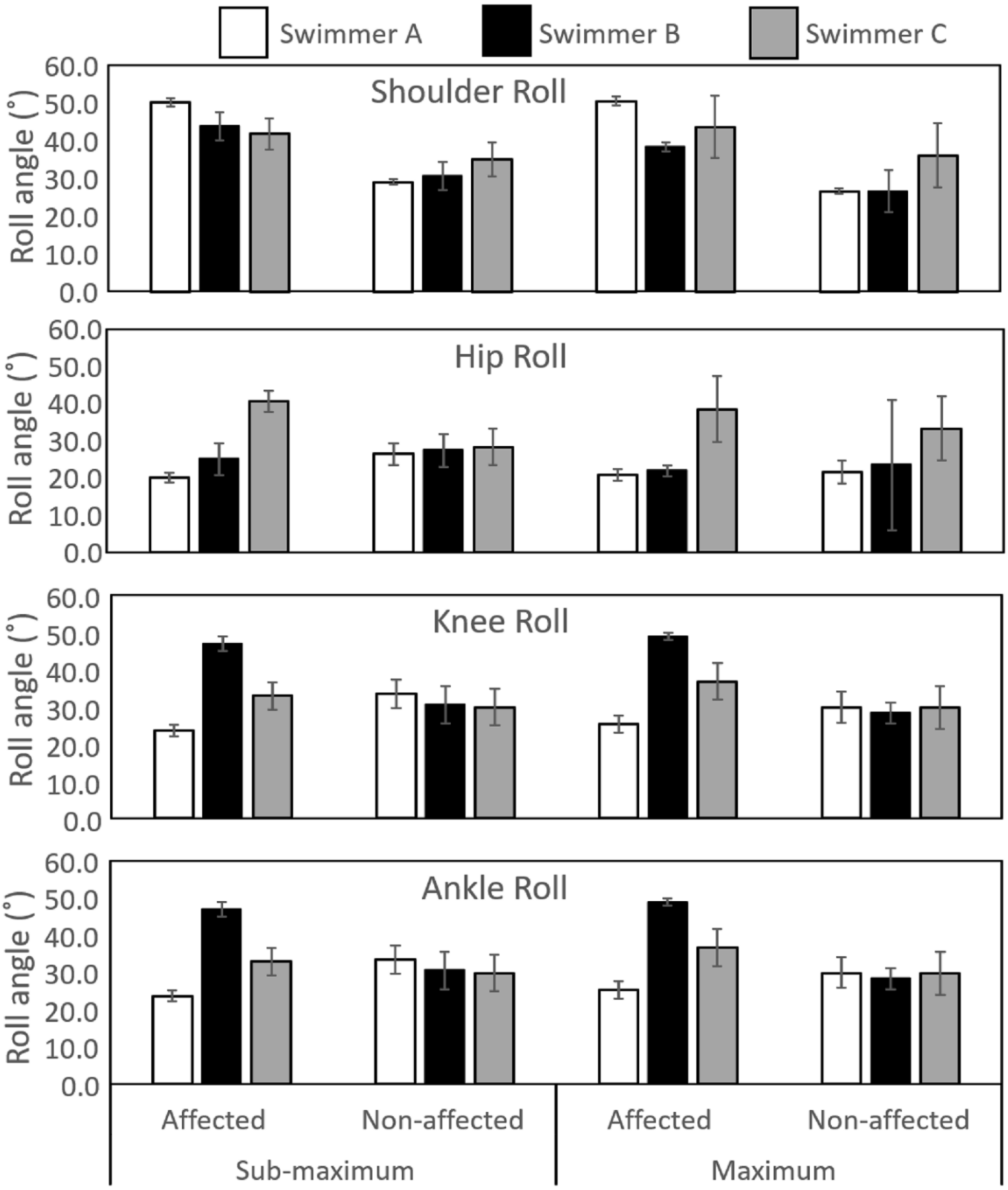
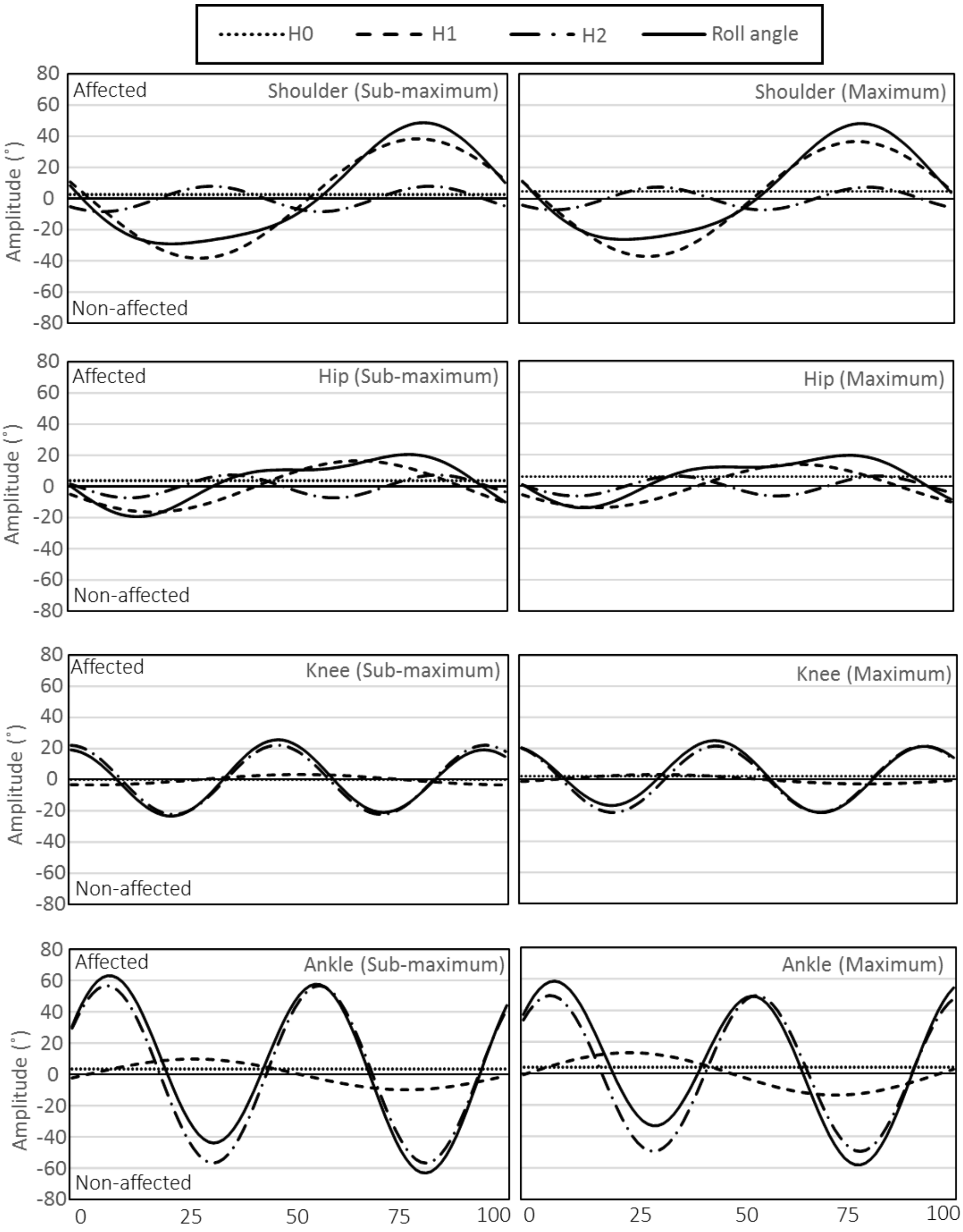
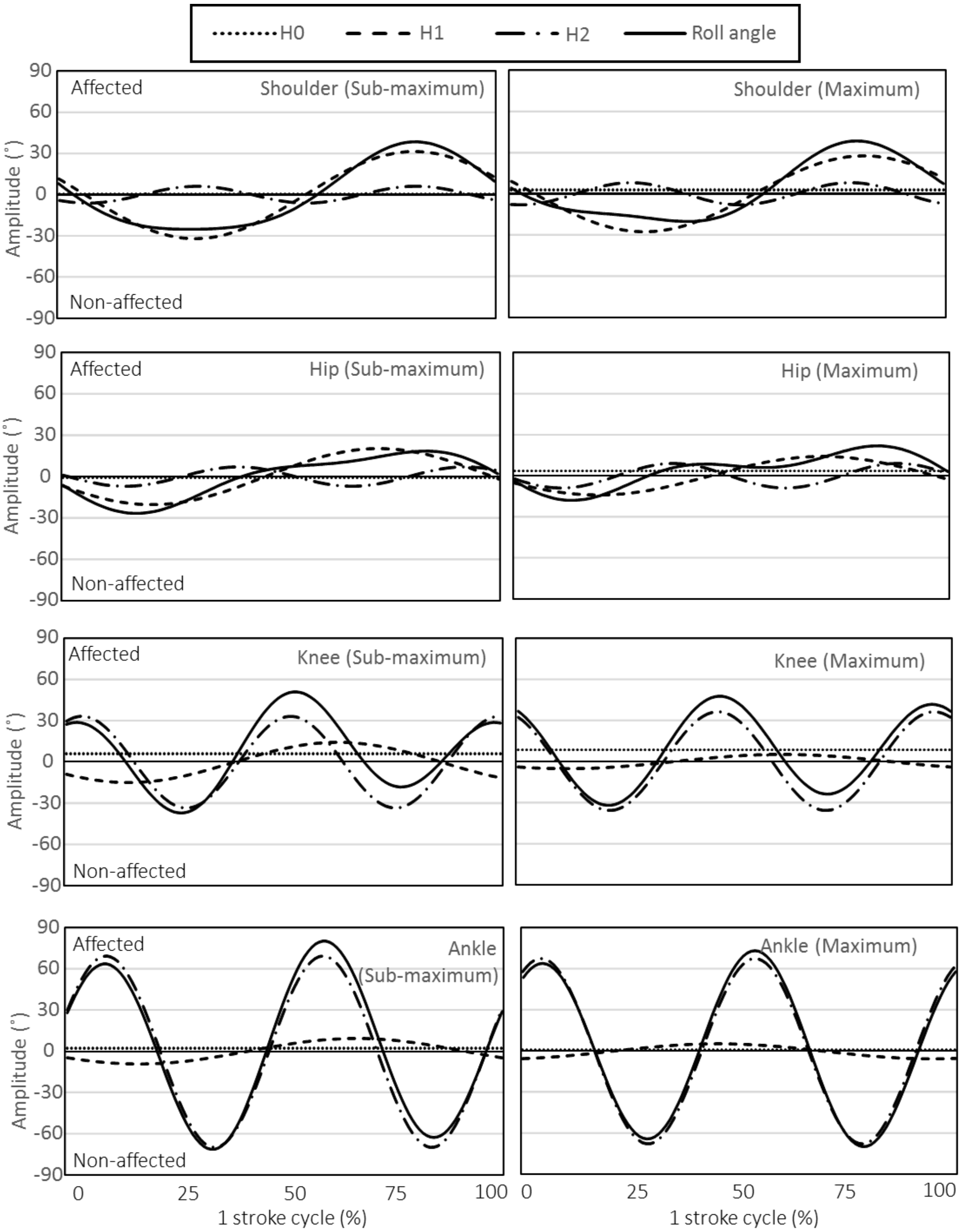


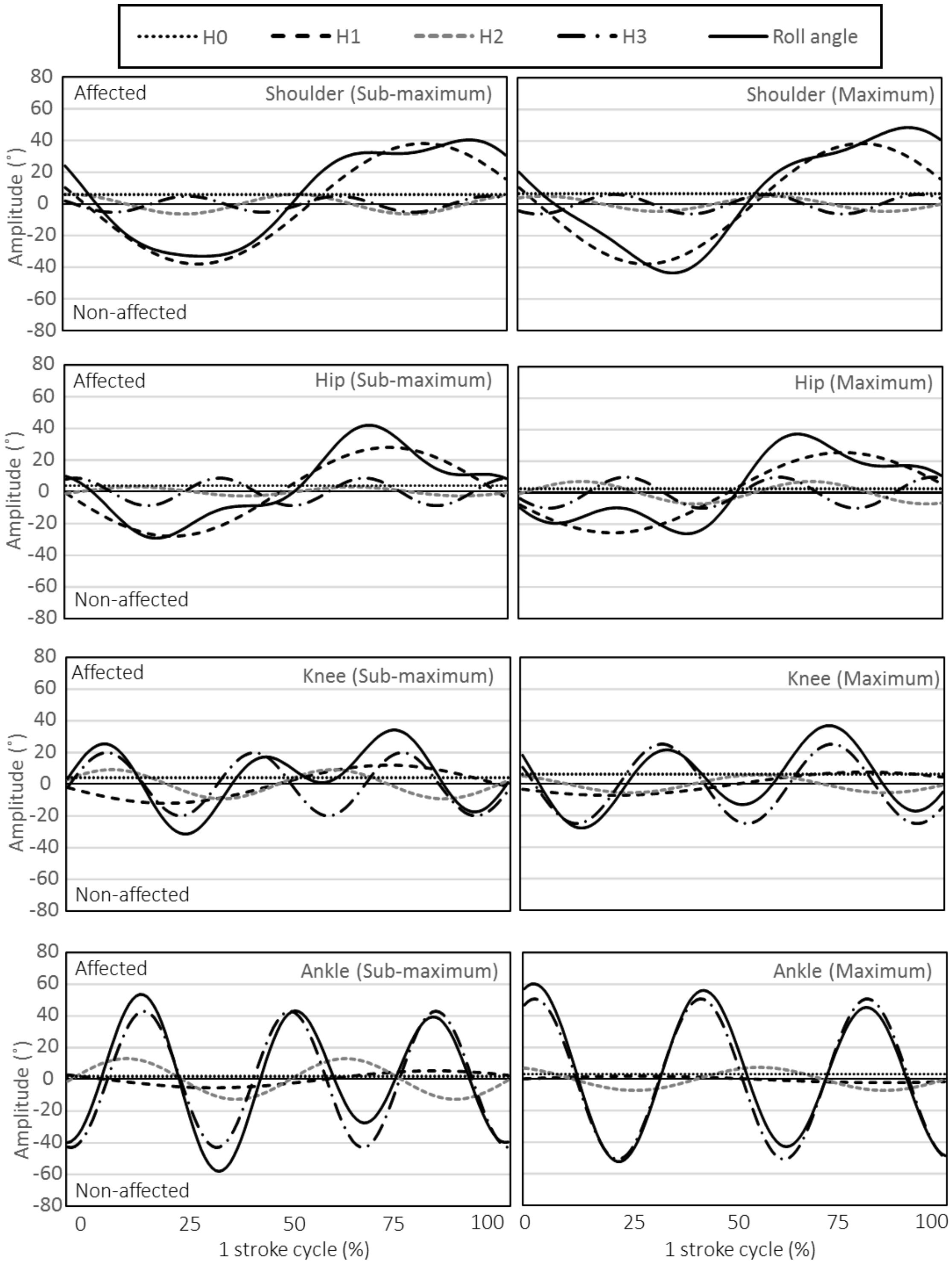
Figure 4. Maximum shoulder, hip, knee, and ankle roll amplitude towards the affected and nonaffected direction.



Appendix I. Original roll angle signals and wave components of shoulder, hip, knee, and ankle during a stroke cycle in Swimmer A at both sub-maximum and maximum trials.



Appendix II. Original roll angle signals and wave components of shoulder, hip, knee, and ankle during a stroke cycle in Swimmer B at both sub-maximum and maximum trials.



Appendix III. Original roll angle signals and wave components of shoulder, hip, knee, and ankle during a stroke cycle in Swimmer C at both sub-maximum and maximum trials.