

On the utility of a rotating swim bench as a freestyle swimming emulator

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

The swim bench is an isokinetic ergometer intended to aid competitive swimming training by replicating the underwater pull of the freestyle stroke. Yet limited literature addresses the biomechanical fidelity of the swim bench relative to in-water swimming (Olbrecht & Clarys, 1983; Piovezan et al., 2019). Further, the lack of body roll on the swim bench may limit simulation fidelity. Accordingly, the Kayak Pro SwimFast swim bench includes a rotating bench setting. Specific changes to a competitive swimmer's kinematics and muscle activation patterns with a rotating setting is unknown. The purposes of this study were assessment of the influences of swim bench settings on kinematics and muscle recruitment, and exploration of the similarity of kinematic data between swim bench and in-water data sets.

Fifteen collegiate and/or national level, male, competitive swimmers completed 8 sets (4 rotating and 4 fixed) of 30 second continuous freestyle stroke pulling on a Kayak Pro SwimFast swim bench. Surface electromyography of 12 right upper limb muscles and bilateral upper limb and torso kinematics were collected. Time-series swim bench kinematic and electromyographic data were compared using statistical parametric mapping, enabling holistic evaluation. The swim bench kinematics were compared to existing in-water data from McCabe (2008).

Few kinematic and electromyographic differences existed between the rotating and fixed swim bench settings. Briefly, left shoulder elevation was higher on the rotating swim bench setting nearing the end of the push leading into the recovery phases of the freestyle swimming stroke ($p = 0.08$). The left shoulder axial rotation approached significance at during the push phase, with a higher internal rotation angle on the rotating setting. Right wrist radial deviation was greater on the fixed setting during the recovery phase ($p = 0.024$). Infraspinatus achieved greater activations on the fixed bench than the rotating during the late pull to early push phases

($p = 0.012$). Despite the device's roll design, no differences existed in shoulder roll between the rotating or fixed setting and, regardless of bench setting, participants laterally flexed the torso, potentially as compensation for the overall lack of roll allowance. The similarities between settings indicated that the rotating setting may not substantially augment the realism of stroke mechanics on the swim bench.

Compared to in-water swimming, the swim bench produced similar elbow flexion angles and maximum vertical depth at the third distal phalanx. However, entry phase duration phase decreased on the swim bench, while the pull, push, and recovery phases increased ($p < 0.0001$). Additionally, the stroke length, mediolateral stroke width range, and vertical stroke depth range, and total shoulder roll decreased ($p = 0.0002$, $p < 0.0001$, $p < 0.0001$, $p < 0.0001$). The differences between the stroke mechanics, lack of entry phase, and addition of the lateral torso flexion on the swim bench are notable considerations for swim bench use in training and research. Swimmers could develop associated habits that reduce swimming economy, and the results suggest that using the swim bench in training may not extrapolate to in-water swimming.

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1.0 Introduction

Competitive swimming is a high intensity, repetitive overhead sport that places immense demand on the upper limb and shoulder joint. At an elite level, competitive swimmers train year-round, swimming between 6 to 12 kilometers daily and accumulate up to 30 000 shoulder rotations weekly (Heinlein & Cosgarea, 2010; Hibberd & Myers, 2013). Of the propulsive forces produced during swimming, the upper limbs contribute more than the legs and are responsible for approximately 90 percent of propulsion (Deschodt et al., 1999). Consequently, the shoulder musculature is continuously loaded throughout training and prone to fatigue (Figueiredo et al., 2013; Pink et al., 1991).

A common complaint among competitive swimmers is shoulder pain. The repetitive stress and propulsive forces produced by the upper body, combined with overuse and high training volume, leave competitive swimmers vulnerable to microtrauma, injury, and shoulder pain (Gaunt & Maffulli, 2012; Heinlein & Cosgarea, 2010; Hibberd & Myers, 2013; Pink et al., 1991). As a result, approximately 46 to 91 percent of competitive swimmer's experience shoulder pain at least once during a season (Bak, 2010; Hibberd & Myers, 2013; Oliveira de Almeida et al., 2015; Sein et al., 2010; Tessaro et al., 2017). Therefore, achieving the most effective swimming mechanics specific to each swimmer is important for producing propulsion and reducing injury development.

To mitigate injury development and enhance performance, coaches, swimmers, and researchers continually evaluate and adjust swimming stroke technique. However, in-water data collection and stroke analysis present unique and, sometimes, unavoidable challenges, such as light refraction and turbulence that can distort image quality and occlude markers (Callaway et al., 2009). As an alternative, the swim bench, an ergometer designed to simulate freestyle

swimming, may be used to avoid underwater data collection and stroke analysis by simulating swimming stroke mechanics on land.

While the swim bench is used for competitive swim training and research, the biomechanical fidelity of swim bench is not well understood. Observations suggest a disparity between the swim bench movement pattern and in-water freestyle swimming (Dalamitros et al., 2014; Muniz-Pardos et al., 2019; Schleihau, 1983; Soares et al., 2012). Additionally, the sparse literature directly evaluating the replication of freestyle swimming muscle activity and 3D kinematics on the swim bench support these observations and demonstrate differences in freestyle stroke trajectory and velocity, muscle activation timing and peak amplitudes (Olbrecht & Clarys, 1983; Piovezan et al., 2019).

The lack of body roll is considered a limiting factor for accurate freestyle stroke simulation on the swim bench. The common stationary bench design prevents competitive swimmers from initiating the body roll at the beginning and end of the underwater phases of the freestyle pull, potentially affecting stroke trajectory and effectiveness because of differing upper limb positioning (Piovezan et al., 2019; Schleihau, 1983; Tanaka et al., 1993). To combat this, the Kayak Pro SwimFast is designed to allow for torso rotation (*SwimBench | Swim Ergo | Swim Simulator*, n.d.). However, the kinematic and electromyographic differences between the rotating and fixed bench settings and the replication of freestyle swimming kinematics per setting is yet to be defined.

Without an extensive understanding of the biomechanical differences and similarities between in-water freestyle swimming and the simulated movement pattern on the swim bench, the safe and proper application of the swim bench is ambiguous. Further, while there is potential that the rotating bench design could better simulate the freestyle stroke movement and muscle

activation patterns, the differences and optimal setting need definition to guide the implementation of the swim bench in training and research.

1.1 Research Purpose

The global purpose of this study was to move towards an understanding of the biomechanical fidelity of swim bench in relation to the in-water freestyle swimming pull and push phases. The primary objective was to compare the upper limb and torso freestyle stroke pull 3D kinematics and muscle activation patterns in elite competitive swimmers on both the fixed and rotating bench settings of the Kayak Pro Swim Fast to each other. . The secondary objective was to evaluate the differences between the swim bench and existing in-water freestyle swimming kinematic data, previously collected for Dr. McCabe's PhD thesis (McCabe. 2008). Because the legs are stationary while using the swim bench, only the torso and upper body were evaluated.

1.2 Research Questions

- 1) Do the 3D kinematics and muscle activation patterns of the upper limb and torso in elite competitive swimmers on the Kayak Pro SwimFast differ between the fixed and rotating bench settings?
- 2) Do the freestyle stroke pull 3D kinematics of the upper limb and torso in elite competitive swimmers differ between in-water swimming and the rotating bench setting of the Kayak Pro SwimFast?
- 3) Do the freestyle stroke pull 3D kinematics of the upper limb and torso in elite competitive swimmers differ between in-water swimming and the fixed bench setting of the Kayak Pro SwimFast?

1.3 Hypotheses

1.3.1 Swim Bench Rotating vs. Fixed Settings

1. The 3D kinematics of the upper limb and torso during the rotating bench setting trials will differ from the fixed bench setting trials.
2. There will be differences in upper limb and torso muscle activation amplitude, timing, and co-activation index between the two settings.

1.3.2 Swim Bench Kinematics vs. McCabe (2008) In-Water Data

3. The 3D kinematics of the upper limb and torso during the swim bench trials will differ from the in-water freestyle pull, regardless of bench setting.

2.0 Literature Review

This chapter provides a background on the current upper body freestyle swimming stroke mechanics used in competitive swimming (Section 2.1) and a review of the swim bench literature regarding the use and evaluation of the swim bench in competitive swimming training and research (Section 2.2).

2.1 Freestyle Stroke Mechanics

2.1.1 Stroke Cycle Phases

For biomechanical analysis, the freestyle stroke cycle is divided into phases. The phases are defined based on arm-trunk angle in the sagittal plane and the position of the arm at definitive points through the stroke (Rouard & Billat, 1990). While there is no standardized division, the commonly used phases are: entry and catch (0° to 45°), pull (45° to 90°), push and exit (90° to 180°) and recovery (180° to 360° or 0°) (Figure 1) (Chollet et al., 2000; Deschodt et al., 1999; Martens et al., 2016). The pull and push phases are the propulsive phases whereas the non-propulsive phases are the recovery and entry (Chollet et al., 2000; Ribeiro et al., 2013).

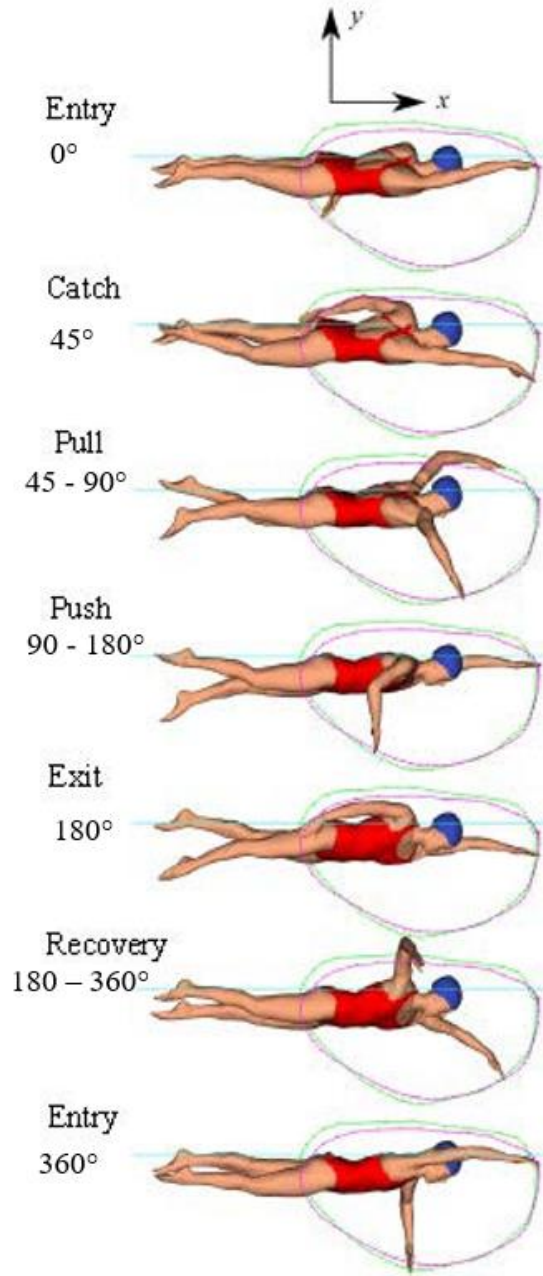


Figure 1. *Phases of the freestyle stroke cycle in the x-y plane (Cohen et al., 2018). Entry phase pictured at 0° to 45° arm-trunk angle in the sagittal plane, pull: 45° to 90°, push: 90° to 180°, and recovery: 180° to 360° or 0° (Chollet et al., 2000; Deschodt et al., 1999; Martens et al., 2016).*

For phase definition, instances during the stroke cycle are often identified in the sagittal plane (Figure 2). Using the horizontal displacement of 3rd distal phalanx and shoulder in sagittal

plane to define stroke instances and phases during one cycle, instances are defined as: first finger entry, the point at which the 3rd distal phalanx enters the water, first-back, the point at which the 3rd distal phalanx begins moving backwards towards the feet, shoulder x, the point at which the 3rd distal phalanx is aligned vertically with the shoulder, end-back, the point when the backward movement ends and the hand is nearby the hip, and recovery, or the second finger entry, where the 3rd distal phalanx re-enters the water a second time after recovery to begin the stroke cycle again (Figueiredo et al., 2013; McCabe et al., 2011; McCabe & Sanders, 2012). The different phases are calculated and identified as the ranges between each of the instances, aligning with the commonly used phases outlined above.

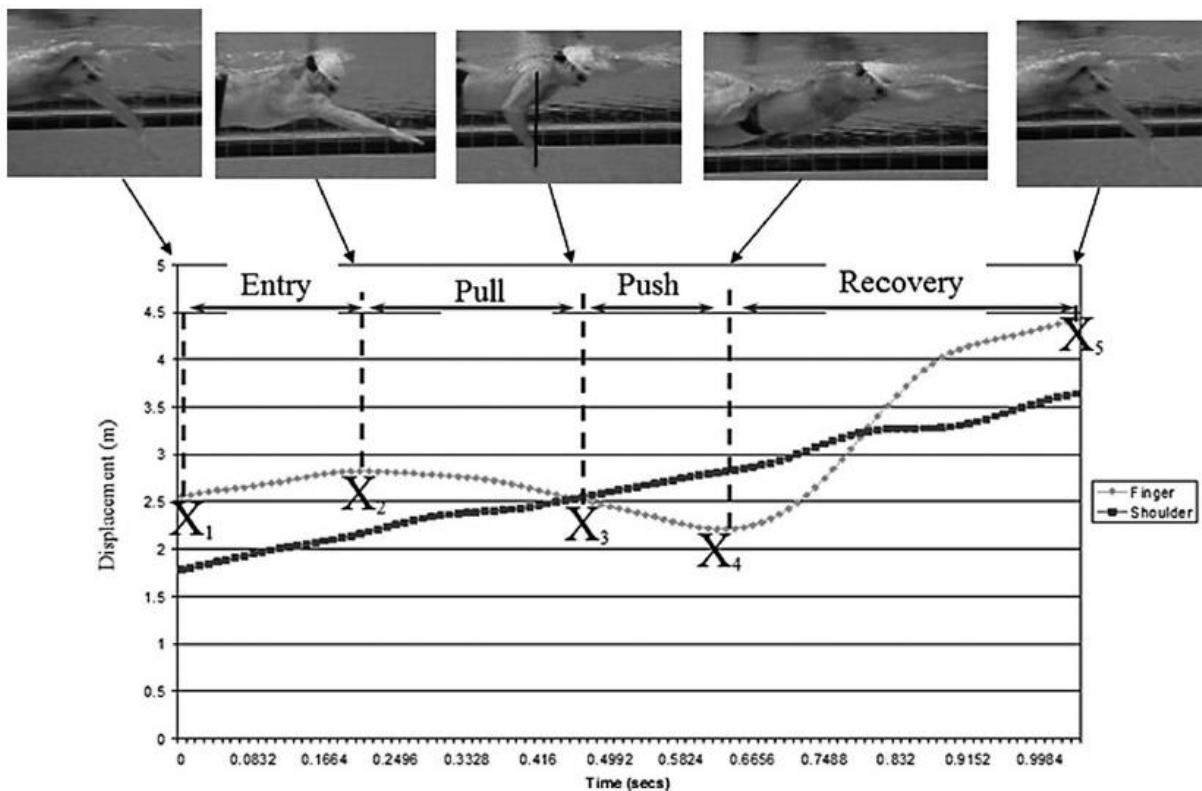


Figure 2. Phase definition and instances through one freestyle stroke cycle (McCabe, 2008). X_1 and X_5 : first finger entry and recovery or second finger entry, X_2 : first-back, X_3 : shoulder x, X_4 : end-back (McCabe, 2008)

2.1.2 Hand Trajectory During the Underwater Phases

During the modern freestyle stroke, the hand trajectory follows a straight path back towards the feet. In male participants, one stroke cycle the pull length amount to 2.0 to 2.2 meters in the x direction (Gonjo et al., 2020; McCabe et al., 2011; Payton et al., 1999). Comparatively, the maximum pull depth is smaller, ranging between 0.65 to 0.79 m in the y direction, and reaches the deepest point during the late pull phase (Figure 2) (Figueiredo et al., 2013; McCabe et al., 2011; Payton et al., 1999; Santos et al., 2020). Unlike the pre-2000's S-shaped pulling technique, the modern freestyle pull incorporates limited inwards sculling during the pull phase and outwards sculling during the push phase (Martens et al., 2015). While the goal is to follow a straight backwards movement, there is some lateral movement resulting in a pull width range between 0.27 to 0.4 meters in the z direction (Figueiredo et al., 2013; McCabe et al., 2011; Payton et al., 1999; Santos et al., 2020).

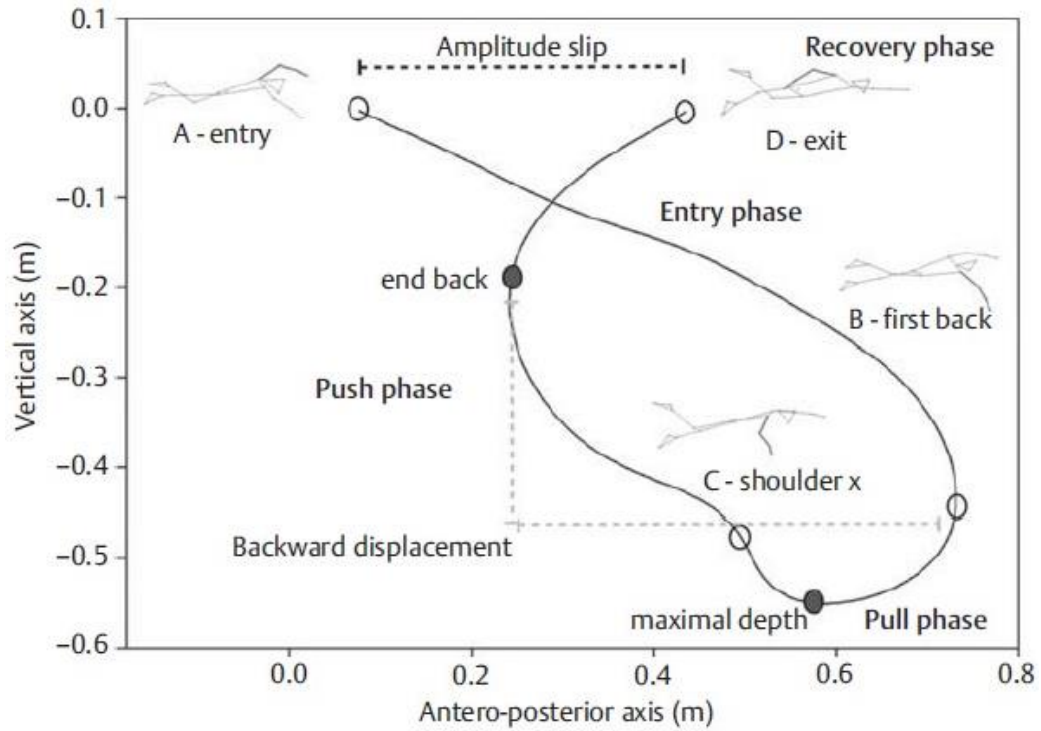


Figure 3. Underwater trajectory of the hand in the x - y plane and corresponding phases during the freestyle pull (Figueiredo et al., 2013).

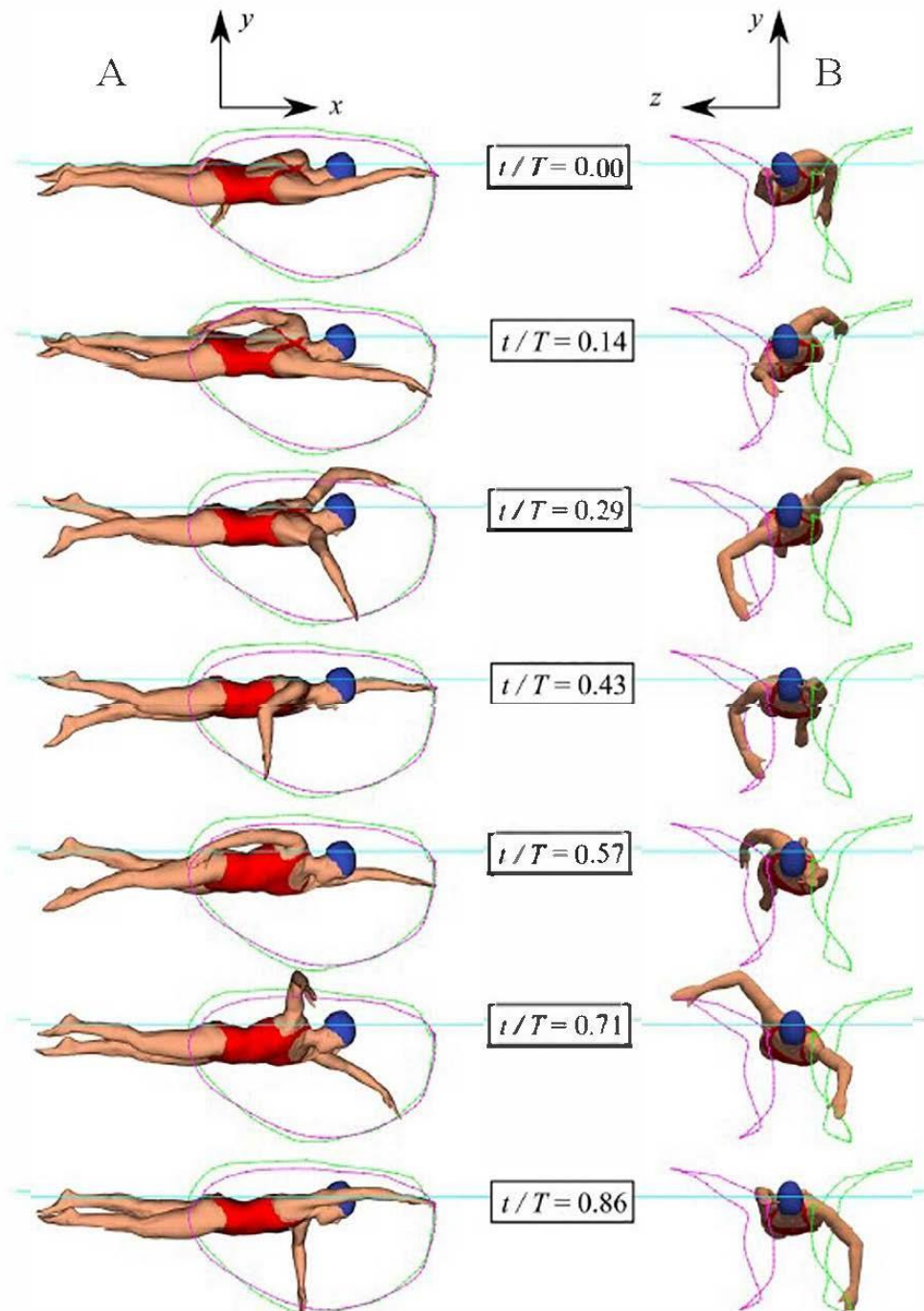


Figure 4. Hand trajectories in x-y plane and z-y plane through freestyle stroke cycle (Cohen et al., 2018). A depicts hand trajectory in the sagittal view and B in the transverse

2.1.3 Hand Velocity and Acceleration During the Underwater Phases

At entry, the hand is at peak velocity, and as the hand encounters the resistance of the water, the hand velocity and acceleration decrease (Gourgoulis et al., 2010; Samson et al., 2019). Through the catch and pull phases, the hand accelerates to reach a steady peak during the pull and push phases (Samson et al., 2019). Throughout the underwater phases of the stroke cycle, the hand is continuously increasing in velocity, reaching a second peak during hand exit (Samson et al., 2019). During the beginning and end of the pull phase, the hand velocity is influenced by internal rotation of the shoulder; however, during the mid-pull, elbow flexion is the primary contributor to hand velocity (Payton et al., 2002). Comparatively, the elbow extension during the push phase contributes to reaching peak hand velocity at exit and the shoulder extension contributes more to hand velocity than any other segment (Payton et al., 2002; Samson et al., 2019).

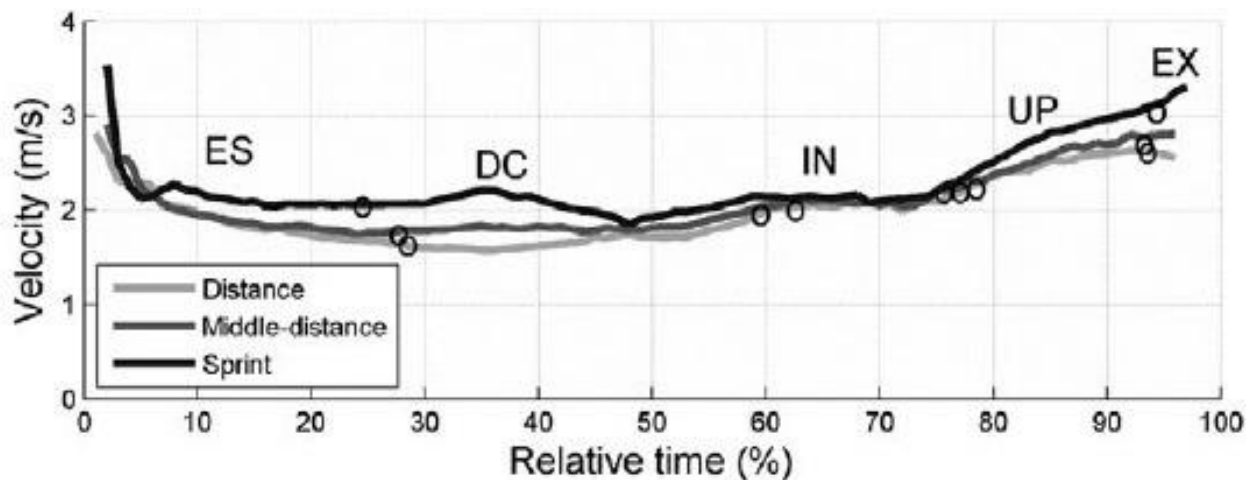


Figure 5. Hand velocity of under water freestyle stroke (Samson et al., 2019). ES indicates the hand entry, DC indicates the catch, IN indicates the pull, UP indicates the push, and EX indicates hand exit.

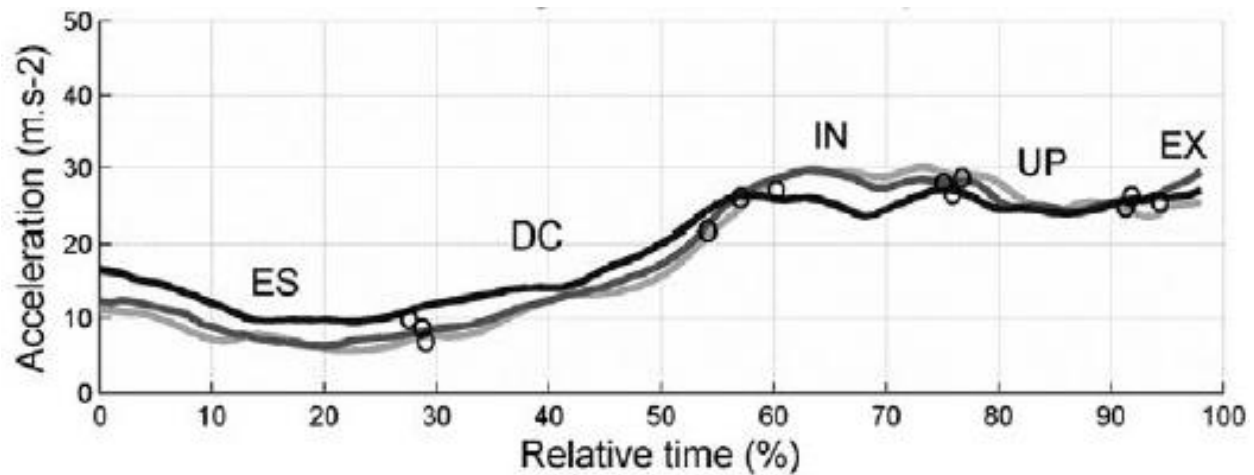


Figure 6. Hand acceleration of underwater freestyle stroke (Samson et al., 2019). ES indicates the hand entry, DC indicates the catch, IN indicates the pull, UP indicates the push, and EX indicates hand exit.

2.1.4 Body Roll

The alternating arm strokes in the freestyle movement pattern are accompanied by body roll, defined as trunk rotation about its longitudinal axis (Psycharakis & Sanders, 2010). Body roll is characterized as a sinusoidal movement, oscillating between left and right arm strokes with maximums at the ipsilateral side entry and catch phase and contralateral side push and exit phase (Kudo et al., 2019; McCabe et al., 2015; Psycharakis & Sanders, 2008; Yanai, 2001). However, the body does not roll as one segment but separately at the shoulders and hips, where the shoulders roll to a greater extent (Psycharakis & Sanders, 2008). In a stroke cycle, the shoulders roll approximately a total amplitude between 97° to 111°, with a maximum between 49° to 54° per side (Andersen et al., 2020; Gonjo et al., 2020; McCabe et al., 2011, 2015; Psycharakis & McCabe, 2011; Psycharakis & Sanders, 2008). Whereas the hips roll approximately a total amplitude between 33° to 57°, with a maximum between 22° to 25° per side (Andersen et al.,

2020; Gonjo et al., 2020; McCabe et al., 2011, 2015; Psycharakis & McCabe, 2011; Psycharakis & Sanders, 2008).

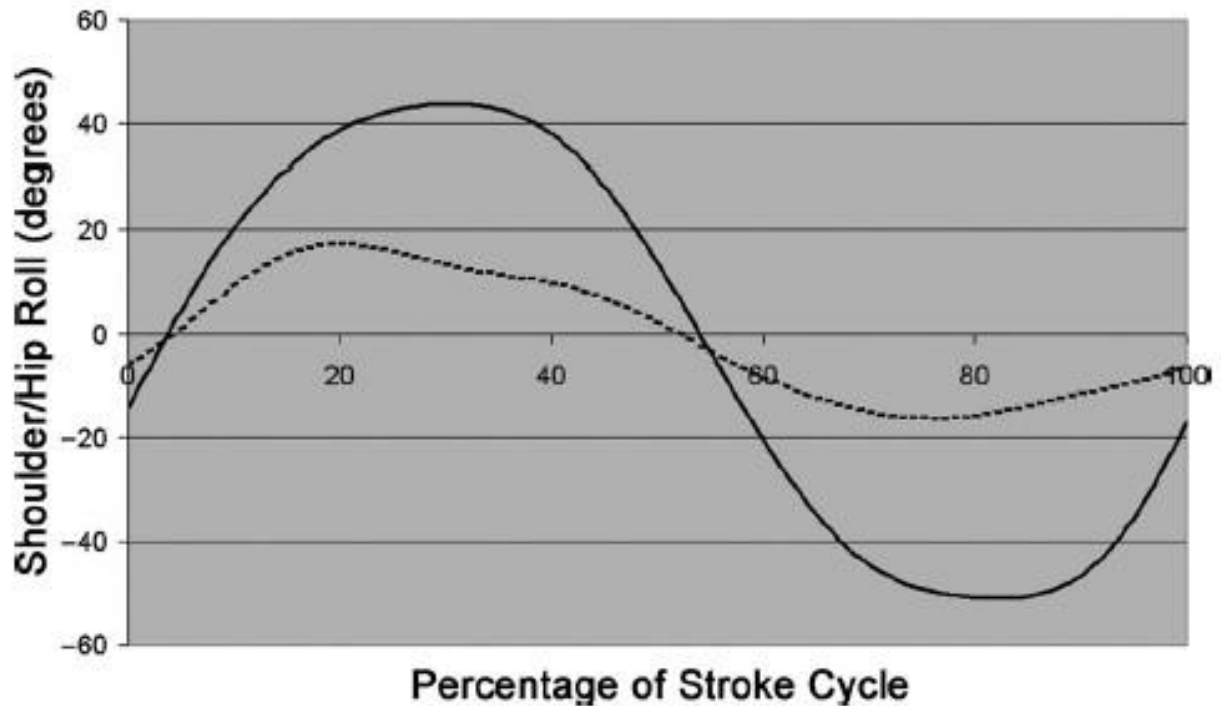


Figure 7. Mean shoulder and hip roll through a freestyle stroke cycle (Psycharakis & Sanders, 2008). Shoulder roll represented by the continuous line and hip roll represented by the dashed line. Roll to the right side represented in the positive y axis and roll to the left represented within the negative y axis (Psycharakis & Sanders, 2008).

Body roll plays an important role in the freestyle stroke movement pattern and propulsion. The body roll facilitates the contralateral arm recovery and breathing actions (Psycharakis & McCabe, 2011; Yanai, 2001). Additionally, there is less passive drag when in a lateral position during the body roll compared to swimming in a prone position (Gonjo et al., 2016). Further, shoulder abduction and roll during the entry phase allows for a long moment arm, which increases the potential production of torque and propulsion during the pull phase (McCabe et al., 2015; Yanai & Hay, 2000). Finally, hand propulsion and velocity can increase when the hand

movement during the late push and exit phase is synchronized with the shoulder roll (Kudo et al., 2017).

2.1.5 Movement Pattern and Muscle Recruitment by Freestyle Stroke Phase

Entry and catch (0° to 45°). At entry, the fingers and hand enter the water first, followed by elbow and arm. During the glide just after entry, the arm reaches forward, lateral to the midline, and extended with slight flexion at the elbow (McCabe et al., 2011). At this point during the stroke, trunk rotation on the ipsilateral side reaches maximum amplitude (Kudo et al., 2019; McCabe et al., 2015; Psycharakis & Sanders, 2008). The supraspinatus, anterior and middle deltoids act to abduct and flex the shoulder, while serratus anterior upwardly rotates and protracts, the upper trapezius elevates, and the rhomboid retracts the scapula (Ceccon et al., 2013; Pink et al., 1991).

As the swimmer initiates the catch, the trunk begins to roll back towards neutral (Kudo et al., 2019; Payton et al., 2002). The forearm starts the backwards pulling movement, grasping the water with the majority of the movement occurring at the elbow and forearm (Payton et al., 2002). The elbow is flexed and in a “high elbow” position to allow for engagement of the propulsive musculature and use of the shoulder as a fulcrum just before the pull (Heinlein & Cosgarea, 2010). During the catch, the biceps brachii and brachioradialis are primarily activated, while the flexor carpi ulnaris (FCU) activates to stabilize the wrist (Clarys & Rouard, 1996; Lauer et al., 2013; Rouard et al., 1997; Rouard & Clarys, 1995).

Pull (45° to 90°). As the catch transitions into the pull, the shoulder begins to move through extension, transitioning from 180° of flexion to 90° (Heinlein & Cosgarea, 2010; Payton et al., 2002). During the pull, the trunk finishes rolling back to neutral (Payton et al., 2002). The high elbow position is maintained, and the elbow moves through a mean range of 40° to 53° of

flexion (Ceccon et al., 2013; Figueiredo et al., 2013; McCabe et al., 2011, 2015; McCabe & Sanders, 2012; Payton et al., 2002). Similar to the late catch, the biceps brachii and brachioradialis are the primary muscles involved in elbow flexion during the pull; however, the triceps are co-activated as an antagonist to the biceps brachii (Lauer et al., 2013; Rouard & Clarys, 1995). The extensor carpi ulnaris (ECU), flexor carpi radialis (FCR) and FCU are activated to stabilize the wrist and transmit the forces from the hand for propulsion (Caty et al., 2007; Figueiredo et al., 2013). To maintain the high elbow position, the shoulder internally rotates and adducts (Yanai & Hay, 2000). The pectoralis major, anterior deltoid, and latissimus dorsi act as the propulsive musculature during the pull phase (Figueiredo et al., 2013; Pink et al., 1991; Rouard & Clarys, 1995). The pectoralis major fires initially to adduct and internally rotate the shoulder, aided by the subscapularis (Pink et al., 1991). Teres minor co-activates, reaching peak activation in the middle of the pull, to promote external rotation of the shoulder and act as an antagonist for the pectoralis major and subscapularis muscles (Pink et al., 1991). The serratus anterior is consistently activated through the pull to upwardly rotate the scapula and maintain joint congruency (Pink et al., 1991). The posterior deltoids are activated to extend the shoulder at the beginning of the pull, while the latissimus dorsi progressively fire to continue extension as the sagittal arm-trunk angle approaches 90° (Clarys & Rouard, 1996; Pink et al., 1991; Rouard & Clarys, 1995).

Push and exit (90° to 180°). The swimmer finishes the last of the underwater propulsive phases by extending both the shoulder and elbow. As the push phase begins, the swimmer rolls the contralateral shoulder and hips away from neutral (Payton et al., 2002). The elbow transitions from the high, flexed, position to extension, sweeping the hand back and past the hip (McCabe et al., 2011). Throughout the push phase, both the latissimus dorsi and triceps brachii are primarily

activated, while the biceps brachii co-activate as an antagonist (Figueiredo et al., 2013; Lauer et al., 2013; Rouard et al., 1997). Again, both the FCU and ECU are active during the push to stabilize the wrist joint as the hand pushes the water backwards (Caty et al., 2007). At hand exit, the rhomboids and upper trapezius are activated to retract the scapula, while the posterior deltoids fire to complete extension and lift the shoulder out of the water (Figueiredo et al., 2013; Pink et al., 1991). At the end of the push phase, the swimmer reaches the second maximum trunk rotation and is in position for over-water recovery (McCabe et al., 2015; Psycharakis & Sanders, 2008).

Recovery (180° to 360° or 0°). The common recovery movement is a high elbow recovery where the elbow leads the movement, and the forearm and hand are relaxed (Yanai & Hay, 2000). During the recovery, the shoulder transitions from extension, abduction, and external rotation when the arm is brought out of the water and overhead, to flexion, adduction, and internal rotation when the arm returns to the entry point (Pink et al., 1991; Yanai & Hay, 2000). The elbow shifts from slightly flexed at exit to flexion in mid recovery, to slightly flexed at entry, never fully reaching extension through the stroke (Heinlein & Cosgarea, 2010). The deltoids fire in sequence through the recovery, where the posterior deltoid fires as the shoulder and arm is lifted out of the water at exit, the middle deltoid and supraspinatus abduct the shoulder, and the anterior deltoid flex the shoulder before entry (Heinlein & Cosgarea, 2010; Pink et al., 1991). The infraspinatus acts to externally rotate the shoulder at the beginning of the recovery, then to depress the humerus, stabilize the shoulder, and acts as antagonist too the subscapularis during the internal rotation of the forearm swing towards entry (Pink et al., 1991). The rhomboids also retract the scapula and upper trapezius and serratus anterior rotate the scapula upward to maintain shoulder joint congruency (Figueiredo et al., 2013; Heinlein &

Cosgarea, 2010; Pink et al., 1991). The bicep brachii act during early recovery to flex the elbow while the triceps act to extend the elbow during late recovery towards entry (Lauer et al., 2013). During late recovery and elbow extension, the biceps brachii also co-activate to act as a brake and control the hand velocity before entry (Lauer et al., 2013). Through the recovery, the fingers are relaxed and wrist is stabilized by the FCU (Rouard et al., 1997).

2.2 Swim Bench

The swim bench is an isokinetic, semi-resistive ergometer that mimics the underwater pull of the freestyle swimming pull. The cyclic movement on the swim bench is suggested to reproduce similar joint angles and muscle activations as in-water swimming (Aspenes & Karlsen, 2012; Muniz-Pardos et al., 2019; Sharp et al., 1982). To produce the freestyle pulling movement on the swim bench, the swimmer lies prone on the bench and pulls against a set of paddles. The paddles are attached by a pulley system to a flywheel that provides adjustable resistance settings (*SwimBench | Swim Ergo | Swim Simulator*, n.d.). Some swim benches allow for torso rotation; however, on most commercially available swim benches, the legs are fixed and do not contribute to the pull (*SwimBench | Swim Ergo | Swim Simulator*, n.d.).

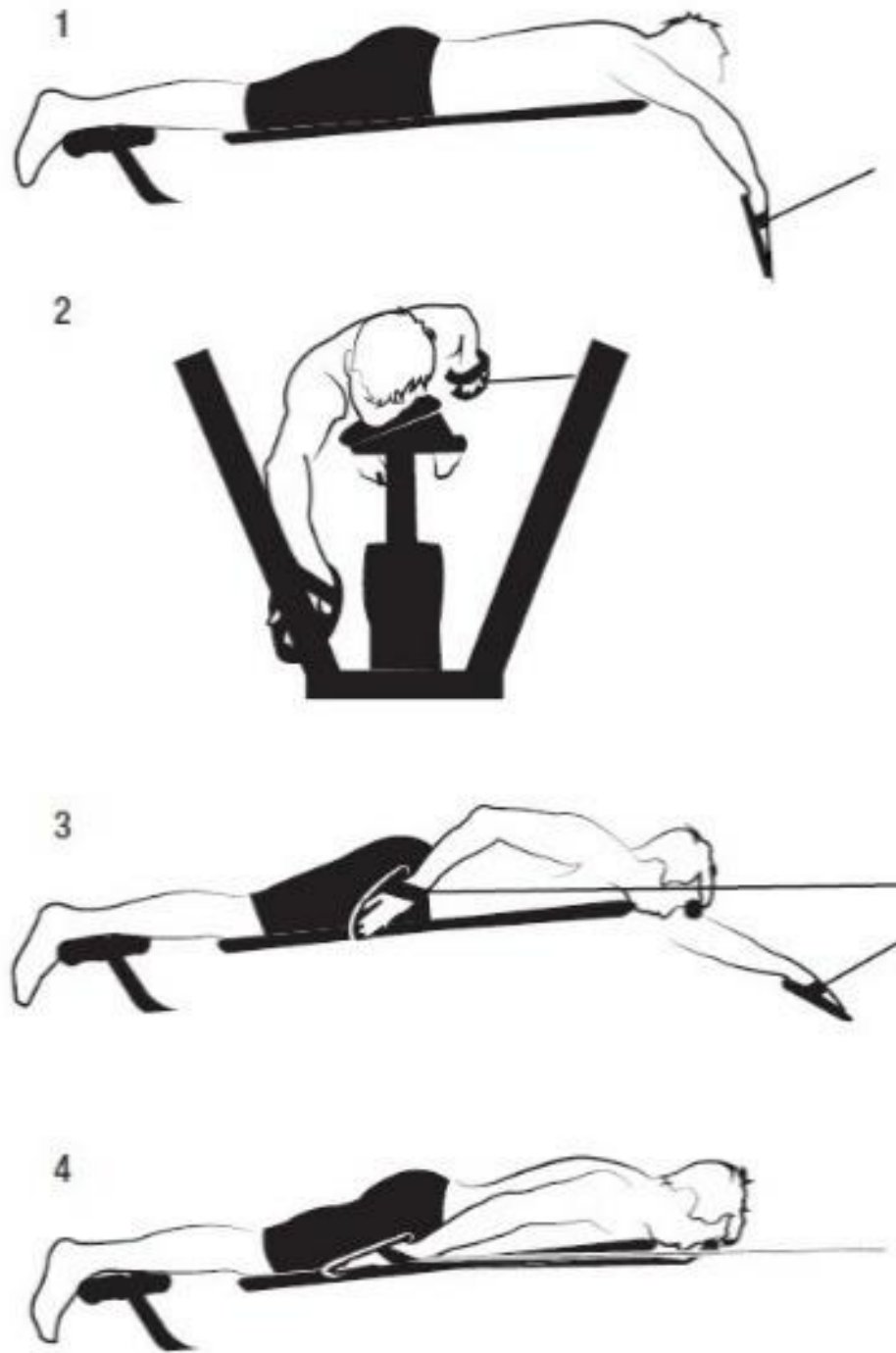


Figure 8. Movement pattern on Kayak Pro SwimFast swim bench (SwimFast Ergometer General instructions, n.d.).

2.2.1 Training Purposes and Effects

For competitive swimming and triathlon purposes, the swim bench is a sport-specific training and assessment tool. The swim bench is advertised as a replacement for in-water swimming when the pool is unavailable, such as during a global pandemic, and is used by swim teams to supplement in-water training (Haddad et al., 2021; Stott, 2018). Additionally, the adjustable resistance allows swimmers returning to sport after injury to maintain their “feel” for the water and movement patterns on the swim bench while progressively increasing the tolerable resistance until equal bilateral upper limb mechanical power is achieved again (Swaine, 1997). Beyond training, clinicians and coaches evaluate performance, mechanical strength, and swimming mechanics with the swim bench (Evershed et al., 2014; Popovici & Suci, 2013; Stott, 2018). As an assessment tool, coaches and clinicians can evaluate bilateral kinematic and power asymmetries with the swim bench and use it as a clinical screening measure for the musculoskeletal imbalances, arm dominance, and unilateral breathing that can increase injury risk (Evershed et al., 2014; Potts et al., 2002). Coaches can also evaluate stroke mechanics and provide real-time qualitative feedback directly to the swimmer on the swim bench because the pulling movement can be adequately seen (Stott, 2018). Further, the swimmer receives immediate sensory feedback from the flywheel resistance when modifying their swimming technique according to the coach’s modifications.

In theory, the swim bench is enticing for supplemental training; however, study results exploring training effects with swim bench use are conflicting. The results of literature investigating the effect of strength, power, and performance training on the swim bench varies, where Popovici & Suci (2013) stated that a strength training intervention on the swim bench resulted in increased strength, yet Sadowski et al. (2012) identified no significant differences or

increases. Similar to Sadowski et al. (2012), Roberts et al. (1991) demonstrated that there are no significant differences in performance, metabolic, power, endurance, and shoulder flexion or extension isokinetic torque post swim bench intervention or between swim bench and control groups. While the results of Sadowski et al. (2012) and Roberts et al. (1991) indicated that the swim bench may be an ineffective training tool, the timing of intervention during the swim season needs to be considered. In the past, high volume training periods have potentially masked training effects in swimmers participating in strength intervention studies and, based on the timing of interventions in Roberts et al. (1991) and Sadowski et al. (2012), first 10 weeks of the season and 6 weeks before championship competitions respectively, the training effects could have also been masked (Lynch et al., 2010; Swanik et al., 2002). Therefore, future research on the training effects of the swim bench may need to be done during off-season training or while pools are unavailable.

2.2.2 Uses in Research

Within research attempts, the swim bench may be used to bypass the complexities of in-water data collection and stroke analysis. Compared to in-water data collection, the swim bench offers a low cost, accessible, and user-friendly alternative. The stationary element of the swim bench allows for a flexible capture volume that permits more than one stroke cycle to be analyzed. The land-based aspect of the swim bench allows for gold standard data collections without worries of waterproofing equipment, introduction of error into signals from water or pool machinery interference, and changes to stroke mechanics because of drag from instrumentation. The most common research use of the swim bench is in swimming power and energetics studies, where the swim bench allows for maximal oxygen consumption and mechanical power output collection in a sport-specific manner (Dalamitros et al., 2014).

2.2.3 Evaluations of the Swim Bench

Past evaluations of the swim bench focused on the relationship between mechanical power output on the swim bench and swimming performance. Research indicates a moderate to strong correlation between maximum mechanical power output on the swim bench and 25-yard sprint time, r of 0.74 to 0.9 (Gatta et al., 2018; Johnson et al., 1993; Sharp et al., 1982). Considering there are no competitive swimming events shorter than 50 meters or yards, this correlation may not be well generalized to swimming training and racing. However, the relationship, r of 0.89, between swim bench critical power output, the maximum power an athlete can maintain over a long period without fatigue, and 1500-m freestyle event time does provide persuasive evidence of a swim bench power-performance relationship (Swaine, 1996). Additionally, Edelmann-Nusser et al. (2004) suggested that individual race performance can be predicted by the changes in mechanical power output measured on the swim bench, evidenced by the correlation between improvements in mechanical power output on the swim bench and 200-meter sprint performance (Edelmann-Nusser et al., 2004). Yet, the relationship between mechanical power output measured on the swim bench and swimming performance is primarily driven by the arms and is stronger with arms only swimming with limited or no leg contribution compared to full-body swimming (Bradshaw & Hoyle, 1993; Gatta et al., 2018; Swaine, 1996, 2000). Therefore, coaches and sport scientists need to be cautious when using the swim bench for research or predicting performance because the swim bench may only represent power generated by the arms and be better aligned with long distance races that involve less leg contribution.

Concerns have been raised regarding the biomechanical fidelity of the freestyle pull on the swim bench compared to in-water freestyle swimming. The swim bench lacks the effect of the water on stroke mechanics and metabolism, such as lift and drag forces, hydrostatic pressure, and

buoyancy (Aspenes & Karlsen, 2012; Cortesi et al., 2018; Muniz-Pardos et al., 2019). Further, the design of the swim bench limits the replicability of the freestyle pull. The isokinetic element of the swim bench does not allow for replication of the changing velocity and acceleration of the upper limb in the water as the swimmer progresses through the different phases of the pull (Arroyo-Toledo & González-Rave, 2017; Soares et al., 2012). The stationary bench and upper body isolation on the swim bench limit the contribution of legs and trunk rotation to the pull as well, which can alter power generation, energetics, and stroke mechanics compared to in-water swimming (Cortesi et al., 2018; Schleihau, 1983; Swaine, 2000; Tanaka et al., 1993).

Differences in stroke mechanics and the pulling movement pattern on the swim bench have also been attributed to changes in the conventional arm stroke trajectory and inadequate elbow positioning control (Bradshaw & Hoyle, 1993; Dalamitros et al., 2014). Finally, the combination of differences in fluid mechanics, resistance, velocity, and movement pattern on the swim bench could potentially load the muscle groups differently to in-water swimming (Cortesi et al., 2018; Olbrecht & Clarys, 1983; Psycharakis & Sanders, 2010; Schleihau, 1983).

Despite the biomechanical uncertainty, there is limited public research available evaluating the 3-dimensional kinematics and muscle activations on the swim bench. With respect to kinematics, Piovezan et al. (2019) concluded that the swim bench could not replace in-water swimming because of the significant differences in stroke trajectory and velocity (Table 1). The hand velocity (m/s), vertical, and mediolateral displacements (m) on the swim bench were all lower compared to in-water swimming, whereas the anteroposterior displacement (m) was greater (Piovezan et al., 2019). Piovezan et al. (2019) suggested that the difference in vertical and mediolateral hand displacements could be attributed to the limited hip roll on the Vasa Swim Ergometer, while the difference in anteroposterior displacement was because of the stationary

aspect of the swim bench. The only similarities identified between in-water freestyle swimming and the swim bench were the stroke frequency and bilateral symmetry of the pull (Piovezan et al., 2019). Additionally, Olbrecht & Clarys (1983) compared muscle activations of different dryland sport-specific strength training tools to in-water swimming, including an isokinetic swim bench. The swim bench was able to reproduce some of the peaks in muscle activity in the FCU, triceps brachii, latissimus dorsi, pectoralis major, anterior deltoid, and posterior deltoid, but not the extensor digitorum, biceps brachii, or external obliques (Figure 9) (Olbrecht & Clarys, 1983). However, the activation timing and amplitude were not replicated completely on the swim bench, where the timing of peaks were delayed, and activation amplitudes lower for greater expended effort compared to in-water swimming (Olbrecht & Clarys, 1983). Based on the two studies, it is evident that the swim bench may not replicate in-water freestyle swimming.

Table 1. *Hand trajectory and velocity differences between swim bench and in-water swimming (Piovezan et al., 2019)*

<i>Hand Displacement</i>	<i>In-Water Swimming</i>		<i>Swim Bench</i>	
	<i>Right</i>	<i>Left</i>	<i>Right</i>	<i>Left</i>
Anteroposterior (m)	0.54 ± 0.19	0.47 ± 0.15	1.22 ± 0.17	1.22 ± 0.23
Mediolateral (m)	0.24 ± 0.12	0.22 ± 0.09	0.19 ± 0.09	0.12 ± 0.05
Vertical (m)	0.47 ± 0.12	0.51 ± 0.16	0.35 ± 0.07	0.40 ± 0.07
Hand Velocity (m/s)	2.87 ± 0.72	2.88 ± 0.76	2.07 ± 0.39	2.04 ± 0.30

EMG - ANALYSIS 'DRY - LAND' EXERCISES OF THE FRONT CRAWL

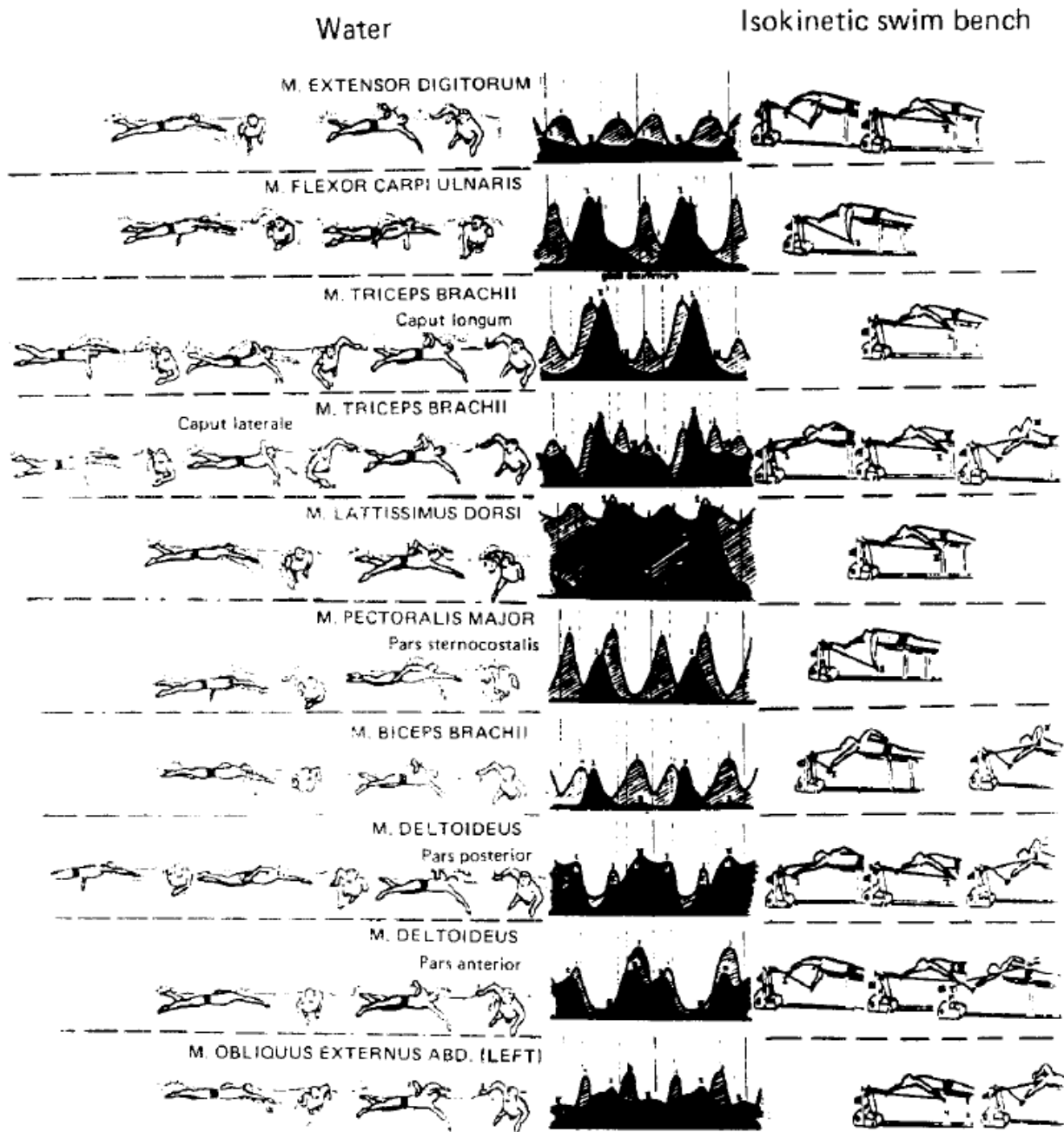


Figure 9. Muscle activation patterns during in-water freestyle swimming compared to the swim bench (Olbrecht & Clarys, 1983). In-water swimming represented in shaded, light grey. Swim bench represented in black.

The studies by Piovezan et al. (2019) and Olbrecht & Clarys (1983), provide a foundation of kinematic and electromyographic similarities and differences between the swim bench and in-water swimming, but further research is still required. Piovezan et al. (2019) used a within subjects design and the results from Piovezan et al. (2019) are compelling; however, the sample size was small (10 participants) and only reported on the hand trajectory and velocity (Piovezan et al., 2019). Future research, including more kinematic measures such as stroke cycle phases, joint angles, shoulder and hip roll, need to be performed to support and augment the results from Piovezan et al. (2019). Additionally, the impact of limited trunk rotation on the freestyle movement patterns and muscle activations on commercial swim benches needs to be quantified. Finally, an in-depth collection of the shoulder and upper limb musculature while executing contemporary swimming technique on the swim bench needs to be completed to understand how the swim bench and lack of rotation effects the muscle loading. While Olbrecht & Clarys (1983) provided results for the propulsive muscles, the freestyle stroke mechanics evaluated used an s-shaped hand trajectory, which is outdated and no longer taught (Martens et al., 2015). Further, the activation patterns of the rotator cuff and scapular stabilizer musculature, and co-activation of propulsive musculature on the swim bench still needs to be investigated.

With the current insufficient knowledge of the differences and similarities between in-water freestyle swimming and the simulated pull on the swim bench, it is questionable if the swim bench can be safely and confidently implemented for research or training purposes. Studies that use the swim bench may not accurately simulate the freestyle movement pattern, and the results of these studies cannot be definitively generalized to in-water swimming. Further, the current use of the swim bench could unknowingly alter a swimmer's stroke mechanics and muscle recruitment which could increase the risk of shoulder injury development. Small changes to

stroke mechanics could influence a swimmer's economy and performance; therefore, for the swim bench to be implemented in training and research, the design and biomechanics of the swim bench need to be understood and reflect the high specificity of the sport.

3.0 Methodology

This chapter describes the methods employed to capture and process the kinematic and electromyographic data on the swim bench (Sections 3.1, 3.2, 3.3). The separate processing for the in-water data, collected by McCabe (2008) is outlined in Section 3.3.3. Data collection methodology for the existing in-water data can be found in Appendix B (McCabe, 2008). Section 3.4 details the statistical analyses between the swim bench settings and between the swim bench and in-water data.

3.1 Swim Bench Participants

Fifteen, male, right-handed, competitive swimmers were recruited from the University of Waterloo and McMaster University varsity swim teams to match the McCabe (2008) existing in-water data and sample size (Table 2). All participants competed at a collegiate and/or national level and were not experiencing shoulder pain within the last year, had no current shoulder injury, or had undergone shoulder surgery. Eleven of the 15 swim bench participants met the inclusion time standards set by McCabe (2008) (50 short course meter (SCM) Freestyle: 24.60, 400 SCM Freestyle: 4:10.00).

Table 2. Participant demographics (mean $\pm$ SD). *D* indicates distance, *S* indicates Sprint. *FR* indicates freestyle, *BR*: breaststroke, *BK*: backstroke, *FLY*: butterfly. Mean 50 m and 400 m freestyle times are based on participant personal bests.

Age (yrs)	Height (cm)	Mass (kg)	Specialty		50 m Freestyle (sec)	400 m Freestyle (min)
20.4 $\pm$ 1.12	181.3 $\pm$ 5.1	78.5 $\pm$ 6.0	8 D/7 S	10 FR/2 BR/ 2 BK/1 FLY	24.77 $\pm$ 1.08	4:15.59 $\pm$ 20.32

3.2 Swim Bench Data Collection

3.2.1 Key Outcomes

The stroke phases of interest for this thesis correspond to the underwater and propulsive components, from hand entry to exit. The recovery phase was omitted from swim bench versus in-water swimming comparisons because this phase is not performed on the swim bench.

The outcome measures of interest were the 3D kinematics and muscle activity of the upper limb and torso through the phases of the freestyle pull. The time spent in each phase (represented in percent stroke cycle (%SC)), stroke length (m), range of and maximum stroke width (m) of the finger, wrist, and elbow, maximum stroke depth (m) of finger, wrist, and elbow, elbow angle per phase instance ($^{\circ}$), elbow angle range ($^{\circ}$) during pull and push phases, and total shoulder and hip roll were calculated to match and compare to the McCabe (2008) data. In addition to the above measures, the angles at the wrist and shoulder joints ($^{\circ}$), and velocity (m/s) and acceleration (m/s^2) of the hand segment, coactivation index of agonist-antagonist muscle pairs, and the time-series and peak shoulder and elbow musculature activation were collected, calculated, and compared between the fixed versus rotating swim bench setting comparisons.

3.2.2 Instrumentation

Swim Bench The Kayak Pro SwimFast swim bench was evaluated for several reasons: commercially availability, inclusion of 9 resistance settings, and provision of distance, time, stroke rate, speed, and power measures usable for ensuring consistency between trials (Figure 10) (*SwimBench | Swim Ergo | Swim Simulator*, n.d.). Further, the Kayak Pro SwimFast bench can be fixed or allow for rotation of the torso, which is unavailable on other commercial swim benches, such as the Vasa Trainer (Figure 11) (*Kayak Pro Comparison Chart*, n.d.). This ability had potential to replicate the freestyle pull more closely.



Figure 10. Kayak Pro SwimFast swim bench (SwimFast Ergometer, n.d.). Kayak Pro SwimFast swim bench used for collections was an older model than pictured and did not include the Halo™ Swim Trainer Template or the full palm handles.



Figure 11. Kayak Pro SwimFast swim bench rotation allowance on rotating bench (SwimFast Ergometer, n.d.). Kayak Pro SwimFast swim bench used for collections was an older model than pictured and did not include the Halo™ Swim Trainer Template or the full palm handles.

The swim bench was fitted to each participant in the entry instance position. The front catch arm width was set to the narrow catch setting. The participant was instructed to lie prone on the bench with the axilla aligned with the top of the bench. The head rest was adjusted so the participant could place their forehead comfortably. The footrests were adjusted so the rollers were 3 cm proximal to the ankle malleolus. The front catch arm width was set to the narrow setting.

Motion Capture Three-dimensional kinematics were captured using Vicon MX20 cameras at a sampling rate of 150 Hz (Vicon, Oxford, UK). A total of 25 individual passive reflective markers were placed bilaterally on the upper limb and torso, according to the anatomical landmarks detailed in the ISB guidelines (Table 3, Figure 12) (Wu et al., 2002, 2005). 7 rigid marker clusters were bilaterally placed on the dorsal side of hand, forearm, arm, and back (Table 3, Figure 12). Markers on the anterior thorax were only used for calibration and removed during swim bench trials.

Table 3. *VICON Marker and Cluster placements (McCabe, 2008; Wu et al., 2002, 2005)s*

<i>Segment</i>	<i>Anatomical Landmark</i>
Thorax	Left & Right Acromion Process (AP)
	Suprasternal Notch (SS)
	Xiphoid Process (XP)
	7 th Cervical Vertebra Spinous Process (C7)
	8 th Thoracic Vertebra Spinous Process (T8)
	5 th Lumbar Vertebra Spinous Process (L5)
	Left & Right Anterior Superior Iliac Spine (ASIS)
	Left & Right Posterior Superior Iliac Spine (PSIS)
	Thoracic (T8) Back Cluster (THOR ₁ , THOR ₂ , THOR ₃ , THOR ₄)
	Lumbar (L5) Back Cluster (LUMB ₁ , LUMB ₂ , LUMB ₃)
Humerus (Right & Left)	Lateral Epicondyle (LE)
	Medial Epicondyle (ME)
	Upper Arm Cluster (UA ₁ , UA ₂ , UA ₃)
Forearm (Right & Left)	Radial Styloid Process (RSP)
	Ulnar Styloid Process (USP)
	Forearm Cluster (FA ₁ , FA ₂ , FA ₃)
Hand (Right & Left)	5 th Metacarpal Joint (MCP ₅)
	2 nd Metacarpal Joint (MCP ₂)
	3 rd Distal Phalanx (DP ₃)
	Dorsal Hand cluster (DH ₁ , DH ₂ , DH ₃)

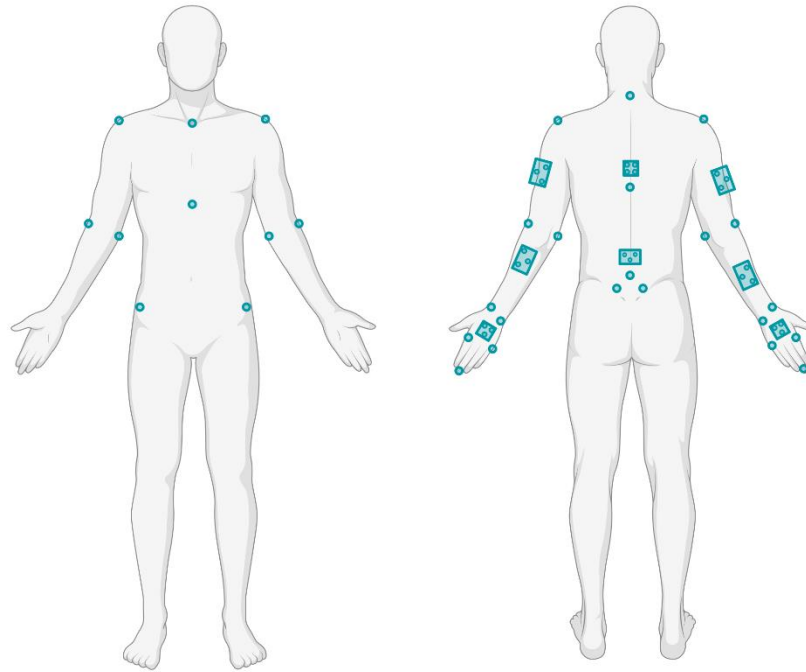


Figure 12. VICON marker placement on anterior and posterior upper limb and trunk (BioRender.com; McCabe, 2008; Wu et al., 2002, 2005). Individual dots indicate individual markers. Rectangles indicate rigid marker clusters.

Electromyography The right upper limb and torso was instrumented unilaterally. Surface electromyography (sEMG) was collected using a wireless Noraxon Telemetry 2400R T2 System (Noraxon USA Inc., Arizona, USA) with a sampling frequency of 1500 Hz. Before electrode placement, the skin was shaved and cleaned with alcohol. Disposable bipolar Ag/AgCl surface electrodes were placed with an inter-electrode distance of 20 mm, following SENIAM guidelines, over a total of 9 muscles using 14 electrode placements: the right serratus anterior, trapezius (upper & lower regions), supraspinatus, infraspinatus, deltoid (anterior, middle, & posterior regions), pectoralis major (clavicular, sternal, & abdominal regions), latissimus dorsi, triceps brachii, and biceps brachii (Table 4, Figure 13). The chosen target musculature are all recognized contributors to propulsion and maintenance of joint stability about the shoulder and

elbow (Lauer et al., 2013; Martens et al., 2015; Pink et al., 1991). The reference electrode was placed on the right clavicle.

Table 4. *Electrode placements (Cram, 2011; Fung et al., 2009).*

<i>Muscle</i>	<i>Region</i>	<i>Placement</i>
Serratus Anterior		Below axillary area at the inferior tip of the scapula and both medial and anterior to the latissimus dorsi.
Trapezius	Upper	Approximately 2 cm posterior to ridge of shoulder, towards back, and halfway between C7 and acromion.
	Lower	Approximately 5 cm below scapular spine, next to medial edge of scapular. Placed on oblique angle, approximately 55°.
Supraspinatus		Directly above spine of scapula over supraspinous fossa, in a horizontal orientation
Infraspinatus		Approximately 4 cm below, running parallel to, the scapular spine and on the lateral aspect of the infraspinous fossa.
Deltoid	Anterior	On the anterior, medial, aspect of the upper arm, approximately 4 cm below the clavicle. Oriented vertically, placed at approximately 25° lateral oblique angle from the vertical.
	Middle	On the lateral aspect of the upper arm, approximately 3 cm below the acromion, oriented vertically.
	Posterior	On the posterior, lateral, aspect of the upper arm, approximately 3 to 5 cm below the lateral border of the scapular spine. Oriented vertically at an oblique, lateral, angle of approximately 25°.
Pectoralis Major	Clavicular	Along the chest wall, 2 cm below the clavicle and medial to the axillary fold. Oriented in an oblique angle towards the clavicle.
	Sternal	Along the chest wall, lateral to the sternum and aligned with the axillary fold.
	Abdominal	Super laterally placed towards the axillary fold, along muscle pennation angle arising between 4 th & 6 th rib.
Latissimus Dorsi		Approximately 4 cm below the inferior tip of the scapular, 50% of the distance between spine and lateral torso. Oriented horizontally with a slight upwards oblique angle of approximately 25°.
Triceps Brachii		Posterior, lateral, aspect of the upper arm over the muscle belly. Oriented vertically, approximately 50% of the distance between the elbow and the acromion.
Biceps Brachii		Anterior aspect of upper arm, over the muscle belly, and oriented vertically.

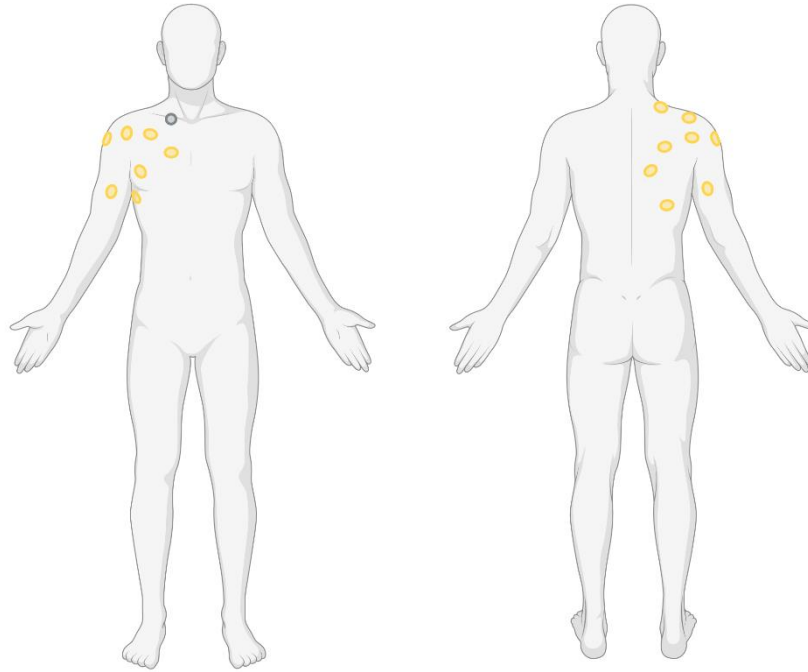


Figure 13. Surface electrode placements on right upper limb and trunk (Biorender.com; Cram, 2011; Fung et al., 2009). Grey circle indicates ground electrode placed on clavicle. Yellow ovals indicate electrode placements.

3.2.3 Collection Protocol

The primary data collection occurred using the swim bench. Participants attended a single session of 2 to 2.5 hours in length (Figure 14).

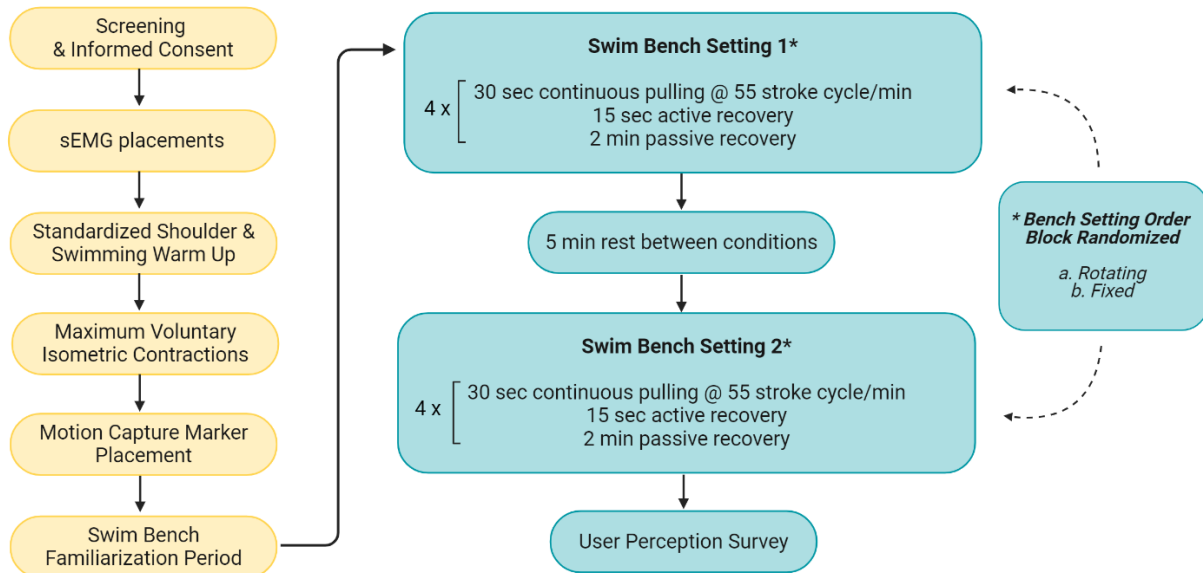
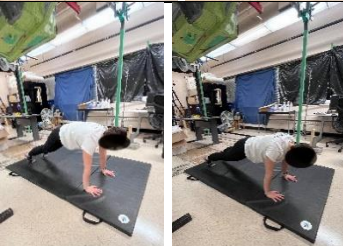


Figure 14. Collection Protocol (BioRender.com). Yellow depicts pre-experimental protocol and teal the experimental protocol.

Pre-Experimental Protocol. After screening for study eligibility, participant's 50 and 400 SCM freestyle personal best times were recorded from Swimming Canada and matched to the McCabe (2008) inclusion protocol. Upon entering the lab, participants reviewed the screening questionnaire, information and consent form, and consent to photography and provided written consent. Afterwards, the participant's height, weight, age, and sex were recorded.

sEMG electrodes were placed unilaterally over the right shoulder and upper arm musculature (Table 4, Figure 13). Following electrode placement, the participant performed a standardized warm up that consisted of exercises commonly performed before swim training (Table 5). Once warmed up, the participant performed 2 sets of 14, 5 second, standardized muscle specific maximum isometric voluntary contractions with allocated rest between (Table 6).

Table 5. Standardized Warm Up

<i>Exercise</i>		<i>Regime</i>
Lunge with thoracic rotation		5 per side
Bird dogs		5 per side
Bear crawls		3 x length of mat (forward & backward)
Scapular push-ups		10
Prone lying I-Y-T-W's	I  Y 	5 per position

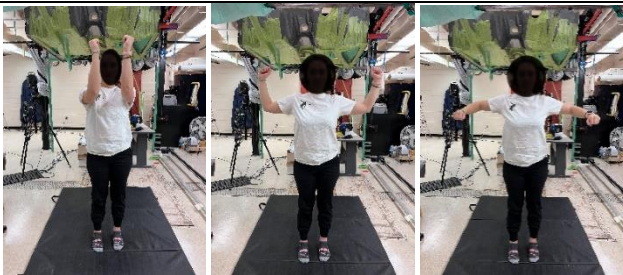
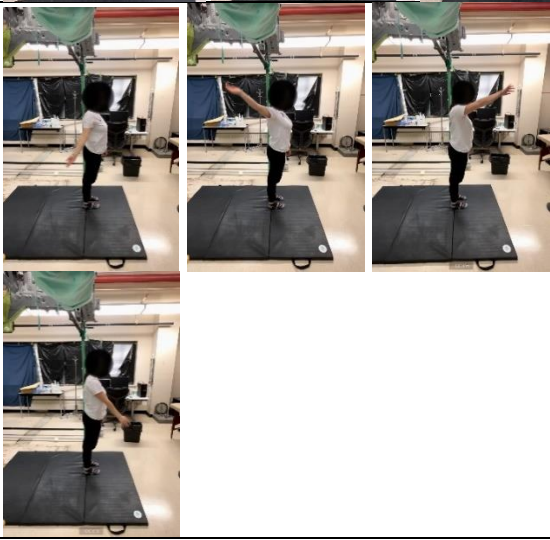
	T W 	
Goal post rotations		10
Shoulder Controlled Articular Rotations		10 per arm

Table 6. Muscle specific maximum voluntary isometric contraction exertions (Boettcher et al., 2008; Cram, 2011; Decker et al., 1999; Ekstrom et al., 2005; Park & Yoo, 2013).

<i>Muscle</i>	<i>Maximum Voluntary Contraction Posture</i>
Serratus Anterior	Elbow at 45° flexion, shoulders at 60° abduction and internally rotated to 45°. Pressing right fist into left palm
Upper Trapezius	Ballistic shoulder shrug
Lower Trapezius	Shoulder at 180° flexion and 120° abduction to align with lower trapezius muscle fibers. Push back against resistance at the wrist
Supraspinatus	Shoulder at 90° flexion, 30° abduction into scapular plane. Push up against resistance at the wrist
Infraspinatus	Elbow at 90° flexion and tucked beside torso with block. Externally rotate against resistance at the wrist
Anterior Deltoid	Shoulder at 90° flexion, thumb pointing superiorly. Push up against resistance at the wrist
Middle Deltoid	Shoulder at 90° flexion and 90° abduction, thumb pointing anteriorly. Push up against resistance at the wrist
Posterior Deltoid	Elbow at 90° flexion, shoulder at 90° flexion and abduction. Push posteriorly with elbow against resistance
Pectoralis Major (Clavicular, sternal, abdominal)	Elbow at 90° flexion, shoulder at 90° flexion and abduction. Hook punch against resistance at the fist
Latissimus Dorsi	Shoulder at 0° flexion with hand pronated. Extend and adduct shoulder while maintaining fixed elbow position against resistance at the hand.
Triceps Brachii	Elbow at 90° flexion and tucked beside torso with wrist pronated. Extend elbow against resistance at the hand
Biceps Brachii	Elbow 90° flexion and tucked beside torso with wrist supinated. Flex elbow against resistance at the hand.

Reflective markers and clusters were placed bilaterally on the upper limb and torso (Table 3, Figure 12). A 5 second static calibration trial was taken in anatomical pose followed by the removal of the right and left anterior superior iliac spine, suprasternal notch, and xiphoid markers.

Before data collection, the swim bench was calibrated according to the participant's mass in kilograms, as instructed in the user manual (*On-Board Console Instruction Manual*, n.d.). The participants were provided time to familiarize with the swim bench and instrumentation by practicing pulling with both arms, alternating arms, with the metronome, and on both swim

bench settings. Participants were provided with as much time as needed for familiarization to reduce the learning effect once performing trials.

Experimental Protocol. The swim bench collection consisted of 8 sets of continuous pulling at a fly wheel resistance setting of 9, corresponding to a stroke velocity of 1.7 m/s, which was comparable to water resistance (Edelmann-Nusser et al., 2004; Ganter et al., 2007). The pulling rate on the bench matched the average stroke frequency from the in-water kinematics study, approximately 55 stroke cycles per minute, calculated as the inverse of time to complete 1 stroke cycle (Figueiredo et al., 2013; McCabe, 2008). A metronome was used to indicate the pull timing and stroke rate for the participant.

Four sets were performed on each of the fixed and rotating bench settings (Figure 15 & 16). The bench setting order was randomized by condition per participant. Each trial consisted of 30 seconds of pulling at 55 stroke cycles per minute (approximately 27 stroke cycles per trial), 15 seconds of active recovery of easy pulling at a self-selected stroke rate, and 2 minutes of passive rest to mitigate fatigue (McCabe, 2008; Toubekis et al., 2008; Toubekis et al., 2011). At baseline and after each trial, participant's rating of perceived exertion (RPE) on the Modified Borg scale was recorded to monitor subjective whole-body effort (Figure 17) (Borg, 1998). Between bench setting blocks, participants passively rested prone laying on the swim bench in the fixed bench setting for 5 minutes to mitigate any potential fatigue carry over to the other setting trials (De Salles et al., 2009).

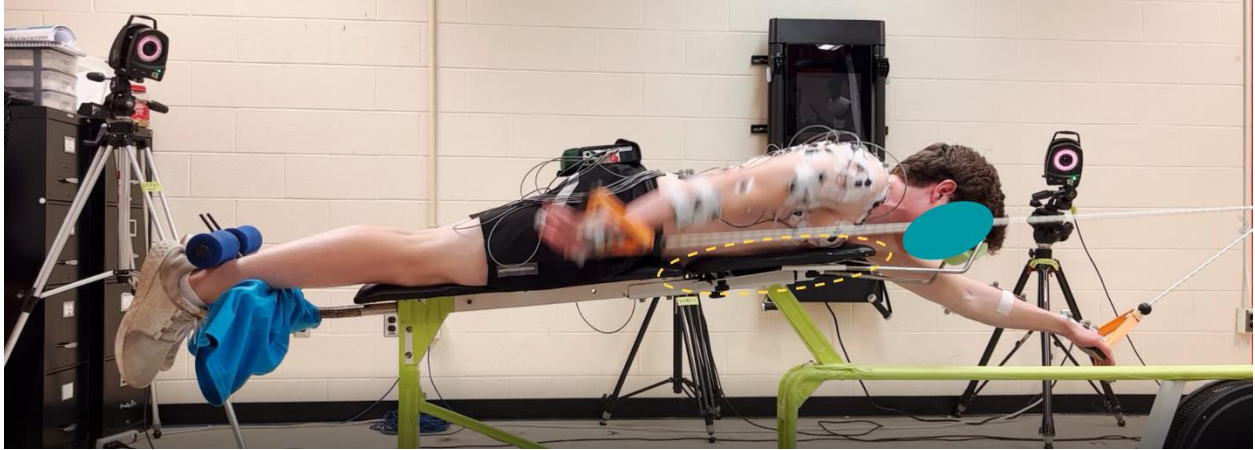


Figure 15. Fixed swim bench setting task. Fixed component circled in dashed yellow.

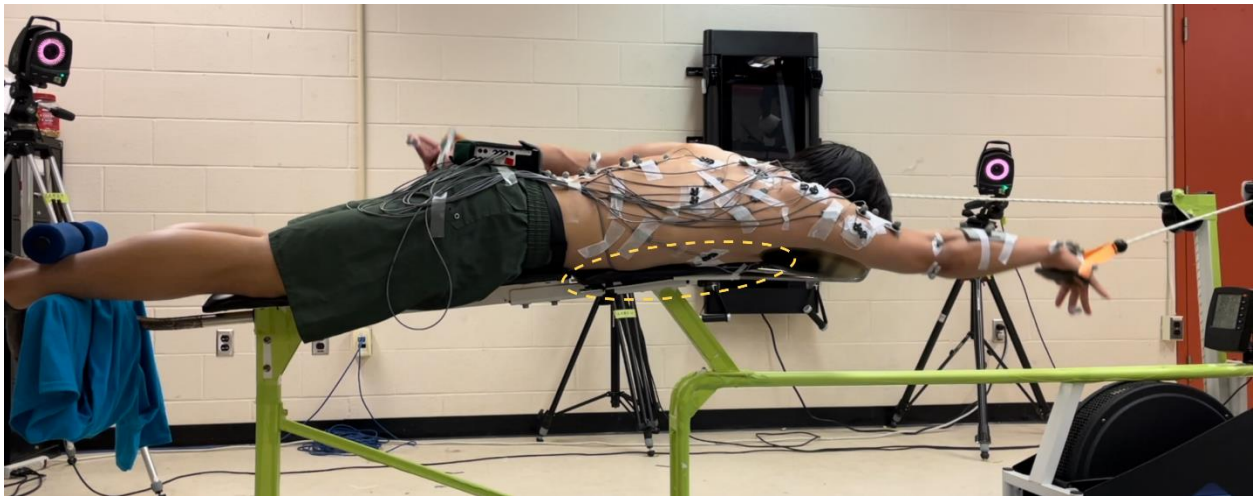


Figure 16. Rotating swim bench setting task. Rotating component circled in dashed yellow.

0	Nothing at all	
0.5	Extremely Weak	(just noticeable)
1	Very Weak	
2	Weak	(light)
3	Moderate	
4		
5	Strong	(heavy)
6		
7	Very Strong	
8		
9		
10	Extremely Strong	(almost max)
•	Maximal	

Figure 17. *Modified Borg Scale (Borg, 1998). Increments not exclusive to whole numbers*

Post-experimental Protocol. Participants completed a custom questionnaire regarding swim bench use history, ease of use, perspectives on the swim bench movement, preferred setting, and likeness to in-water swimming (Appendix A).

3.3 Data Processing

3.3.1 Motion Capture Processing

Raw motion capture data were labelled and trimmed using Vicon Nexus 2.6.1. (Vicon, Oxford, UK). Gaps less than 1 second of data were filled using the pattern fill and rigid body fill functions in the Vicon software. The 3 most complete trials per setting were taken for processing and the middle 6 stroke cycles, 3 per arm and a capture window of 5.45 seconds, per trial were exported. Trials were chosen if the participant achieved the 55 stroke cycles per minute stroke rate and there was no full marker set drop out.

Kinematic data were low pass filtered with a 4th order, zero-lag, Butterworth filter with a cut-off frequency of 4 Hz and rotated to ISB axes (McCabe, 2008; Wu et al., 2002, 2005). The right and left ASIS, suprasternal notch, and xiphoid process markers were reconstructed from the

thoracic and lumbar clusters using local coordinate system based interpolation (Howarth & Callaghan, 2010). The trials were divided into 6 separate stroke cycles, 3 per side, using the entry instance of the 3rd distal phalanx (Figure 12, Table 7). The stroke cycles were time normalized to %SC and the 3 trials per side and setting were ensemble averaged to produce 1 time series data set per setting.

The freestyle stroke cycle was divided into 4 instances and 4 phases (Figure 12, Table 7 & 8). The instances were determined using the horizontal and vertical finger displacement relative to the shoulder and C7 marker in the sagittal plane to harmonize with an existing in-water dataset (McCabe, 2008) (Figure 18). Phases were calculated as the movement sections between the identified instances, and the durations of each phase represented in % SC. While the recovery phase was omitted from between swim bench setting kinematic analyses, for comparison with the McCabe (2008) stroke phases, the recovery phase on the swim bench was calculated.

Table 7. Freestyle stroke instance identification during a stroke cycle (Figueiredo et al., 2013; McCabe, 2008; McCabe & Sanders, 2012)

<i>Stroke instance</i>	<i>Identification</i>
First & second finger entry	3 rd distal phalanx reached the vertical position equal to the C7 marker.
First back	3 rd distal phalanx began to move towards the feet. When the x plane velocity became positive after crossing zero
Shoulder-x	Displacement of the 3 rd distal phalanx aligned with the shoulder joint position in the x plane
End back	3 rd distal phalanx began to move towards the head. When the x plane velocity became negative after crossing zero

Table 8. Freestyle stroke phase calculation during 1 stroke cycle (Chollet et al., 2000; Deschodt et al., 1999; Martens et al., 2016).

Freestyle stroke phase	Definition	
Entry	Initial entry to first back	$\text{first back \% SC} - \text{initial entry \% SC}$
Pull	First back to shoulder-x	$\text{shoulder } x\% \text{ SC} - \text{first back \% SC}$
Push	Shoulder-x to end back	$\text{end back \% SC} - \text{shoulder } x\% \text{ SC}$
Recovery	End back to re-entry	$\text{re entry \% SC} - \text{end back \% SC}$

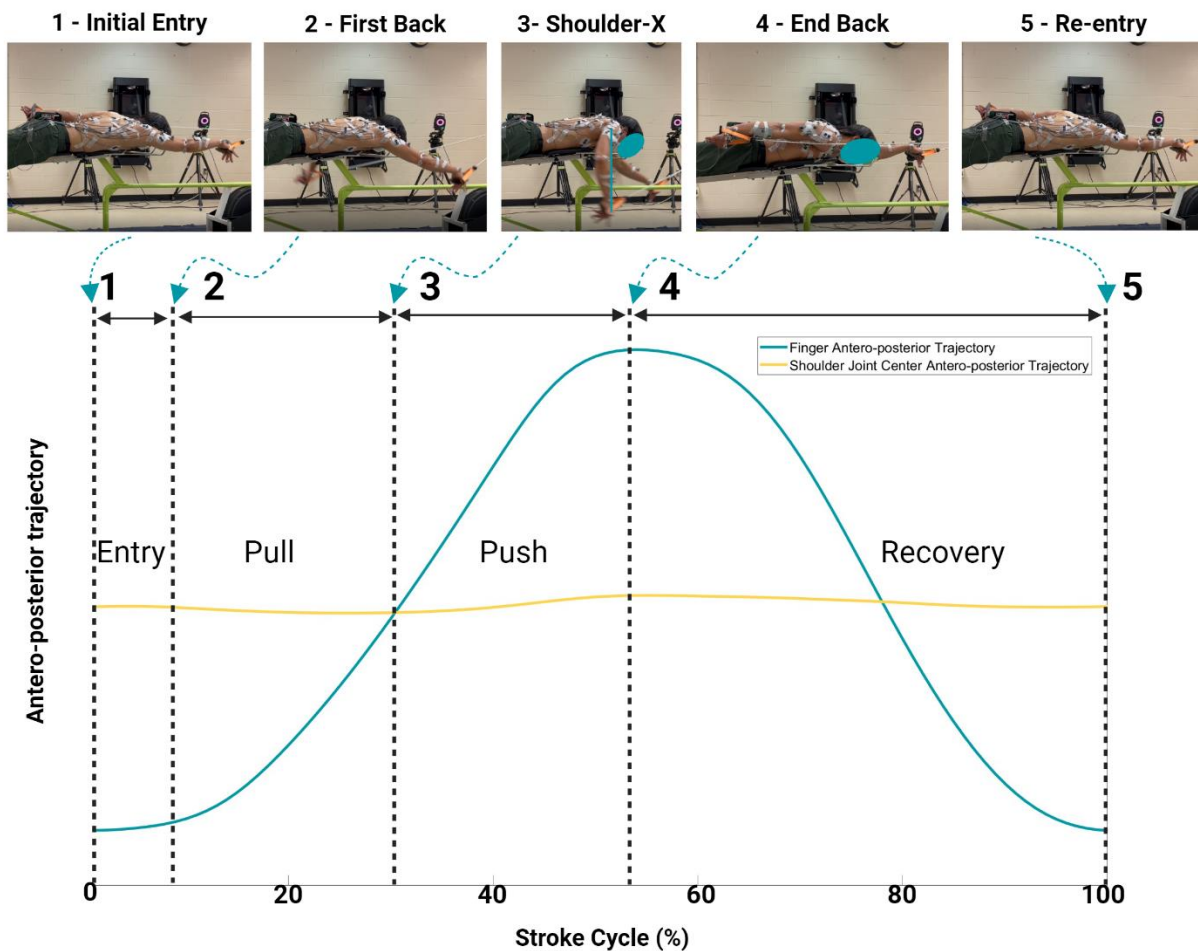


Figure 18. Swim bench phase definition and instances through one freestyle stroke cycle using the anteroposterior trajectory (m) of the 3rd distal phalanx and shoulder joint center (BioRender.com, McCabe, 2008). 1) Initial first finger entry 2) first-back 3) shoulder x 4) end-back 5) first finger re-entry (McCabe, 2008)

Stroke length, width and depth, and hand segment velocity and accelerations were calculated within the global coordinate system (Figures 10 & 11). Stroke length was calculated

as the anteroposterior (X) displacement of the 3rd distal phalanx from finger entry to end-back phase instances. Stoke depth was calculated as the vertical (Y) displacement (m) of the 3rd distal phalanx, wrist joint center, and elbow joint center. Stroke width was calculated as the mediolateral (Z) displacement (m) of the 3rd distal phalanx, wrist joint center, and elbow joint center in relation to the torso center line between C7, T8, and L5 landmarks. Hand segment translational velocities and accelerations were calculated using the central differences technique.

The joint centers for the wrist and elbow were defined based on Wu et al. (2005) the glenohumeral joint center from Nussbaum & Zhang (2000) and hip joints from Bell et al. (1989). The location of glenohumeral joint center was approximated by subtracting 60 mm along the vertical axis of the torso from the acromion marker location (Nussbaum & Zhang, 2000). The right and left hip joint centers were calculated as the ASIS location plus an identified percentage (30% distal, 14% medial, and 22% posterior) of the ASIS-to-ASIS separation distance in Bell et al. (1989) (Eq. 1, Eq. 2, Eq. 3). Following ISB guidelines, local coordinate systems and unit vectors for the hand, forearm, humerus, and thorax were defined (Table 9) (Wu et al., 2005).

$$Hip\ Joint_x = ASIS_x + (0.14 \times ASIS\ Separation\ distance) \quad [Eq. 1]$$

$$Hip\ Joint_y = ASIS_y + (-0.3 \times ASIS\ Separation\ distance) \quad [Eq. 2]$$

$$Hip\ Joint_z = ASIS_z + (-0.22 \times ASIS\ Separation\ distance) \quad [Eq. 3]$$

Table 9. *Segment coordinate systems (Wu et al., 2005).*

<i>Segment</i>	<i>Origin</i>	<i>Local Coordinate System</i>
Thorax	Suprasternal notch	Y_t = line connecting the midpoint between the xiphoid process and 8 th thoracic vertebra and the midpoint between the suprasternal notch and 7 th cervical vertebra. Directed superiorly Z_t = line perpendicular to the y -axis plane. Directed rightward X_t = common perpendicular line between Z_t and Y_t axes. Directed anteriorly
Humerus	Glenohumeral joint center	Y_{h1} = line connecting the glenohumeral joint and the midpoint between the lateral and medial epicondyles. Directed to the glenohumeral joint. X_{h1} = line perpendicular to the Y_h plane. Directed anteriorly Z_{h1} = common perpendicular line between X_h and Y_h axes. Directed rightward
Forearm	Ulnar styloid	Y_f = line connecting the ulnar styloid and the midpoint between the lateral and medial epicondyles. Directed proximally X_f = line perpendicular to the plane through the ulnar and radial styloids and the midpoint between the lateral and medial epicondyles. Directed anteriorly Z_f = common perpendicular line between Y_f and X_f axes. Directed rightward
Hand	Wrist joint center	Y_{h2} = line between the midpoint between the ulnar and radial styloid and the midpoint between the fifth and first metacarpals X_{h2} = line perpendicular to the Y_{h2} plane. Z_{h2} = the common perpendicular line between Y_{h2} and X_{h2} axes.

Intersegmental angles for the wrist, elbow, shoulder, and trunk were generated as Euler rotation sequences of local coordinate systems defined for the forearm, arm, thorax, and pelvis (Table 10) (Phadke et al., 2011; Wu et al., 2002, 2005). For the wrist, elbow, and torso a Z-X-Y sequence was followed (Eq. 4), whereas a X-Z-Y was followed for the shoulder (Eq. 5) (Phadke et al., 2011; Wu et al., 2002, 2005).

$$R = R_z(\beta)R_x(\alpha)R_y(\gamma) \quad [\text{Eq. 4}]$$

$$R = \begin{bmatrix} \cos\gamma\cos\alpha - \sin\beta\sin\alpha & \cos\gamma\sin\alpha + \sin\gamma\sin\beta\cos\alpha & -\sin\gamma\cos\beta \\ -\cos\beta\sin\alpha & \cos\beta\cos\alpha & \sin\beta \\ \sin\gamma\cos\alpha + \cos\gamma\sin\beta\sin\alpha & \sin\gamma\sin\alpha - \cos\gamma\sin\beta\cos\alpha & \cos\gamma\cos\beta \end{bmatrix}$$

$$R = R_x(\alpha)R_z(\beta)R_y(\gamma) \quad [\text{Eq. 5}]$$

$$R = \begin{bmatrix} \cos\gamma\cos\alpha & \cos\gamma\sin\alpha\cos\beta + \sin\gamma\sin\beta & \cos\gamma\sin\alpha\sin\beta - \sin\gamma\cos\beta \\ -\sin\alpha & \cos\alpha\cos\beta & \cos\alpha\sin\beta \\ \sin\gamma\cos\alpha & \sin\gamma\sin\alpha\cos\beta - \cos\gamma\sin\beta & \sin\gamma\sin\alpha\sin\beta + \cos\gamma\cos\beta \end{bmatrix}$$

Table 10. Rotation sequences for joint angle calculations and associated interpretations (Phadke et al., 2011; Wu et al., 2005) Rotation axes denoted with $e1$, $e2$, and $e3$.

Joint	Sequence	Rotation	Description
Thorax to Global	Z-X-Y	$e1$ (α): Flexion & extension	Axis coincident with the global coordinate system z-axis. Extension (+) Flexion (–)
		$e3$ (γ): Axial rotation	Axis coincident with the thorax y-axis. Left (+) Right (–)
		$e2$ (β): Lateral flexion	Common perpendicular axis to $e1$ and $e3$. Right (+) Left (–)
Humerothoracic	X-Z-Y	$e1$ (α): Humeral elevation	Axis coincident with the thorax x-axis. Elevation (+) Depression (–)
		$e3$ (γ): Axial rotation	Axis coincident with the humeral y-axis. Internal rotation (+) External rotation (–)
		$e2$ (β): Plane of elevation	Common perpendicular axis to $e1$ and $e3$. Horizontal flexion (+) Horizontal extension (–)
Elbow	Z-X-Y	$e1$ (α): Flexion & extension	Axis coincident with the humeral z-axis Flexion (+) Hyperextension (–)
		$e3$ (γ): Axial rotation	Axis coincident with the forearm y-axis Pronation (+) Supination (–)
		$e2$ (β): Carrying angle	Common perpendicular axis to $e1$ and $e3$.
Radiocarpal	Z-X-Y	$e1$ (α): Flexion & extension	Axis coincident with the forearm z-axis. Flexion (+)
		$e3$ (γ): Rotation	Axis coincident with the hand y-axis Pronation (+), neutral (0°) Supination (–)
		$e2$ (β): radial & ulnar deviation	Common perpendicular axis to $e1$ and $e3$. Ulnar deviation (+) Radial deviation (–)

The shoulder and hip roll angles were calculated as the arctangent of the joint center unit vector y component divided by the z component (McCabe, 2008). Total shoulder and hip roll were calculated as the magnitude between the maximum and minimum roll angles achieved throughout the stroke cycle (Eq. 6, Eq. 7). Due to differences in marker set up and for

comparison between bench setting and in-water data, an additional elbow flexion angle was calculated using the arccosine of the dot product between the forearm and the humerus unit vector (Eq. 8) (McCabe, 2008).

$$\text{Shoulder roll} = \text{atan}(\text{Shoulder_y}/\text{Shoulder_z}) \quad [\text{Eq. 6}]$$

$$\text{Hip Roll} = \text{atan}(\text{Hip_y}/\text{Hip_z}) \quad [\text{Eq. 7}]$$

$$\text{Elbow } \theta = \text{acos}(\text{forearm} \cdot \text{humerus}) \quad [\text{Eq. 8}]$$

3.3.2 Electromyography Processing

Raw sEMG was bandpass filtered between 30 to 500 Hz with a 4th order, zero-lag, Butterworth filter to reduce ECG artifact (Drake & Callaghan, 2006). The signals were full wave rectified, linear enveloped with a low pass 4th order, zero lag Butterworth filter at a 3 Hz cut-off, and normalized to muscle specific peak maximum voluntary isometric contraction amplitudes collected during experimental set up (Table 4). Each muscle was time normalized to %SC based on the stroke cycles and entry instances identified in the kinematics processing. The processed EMG for the 3 stroke cycles per trial and trials per setting were ensemble averaged to produce 1 time series amplitude data set for each setting.

sEMG for the pectoralis major regions, infraspinatus, bicep brachii and triceps brachii were integrated per unit time (iEMG) for coactivation index calculations. The pectoralis major regions and infraspinatus, and bicep brachii and triceps brachii pairs were analyzed specifically because each pairing is considered an agonist-antagonist pairing during the freestyle stroke pull (Caty et al., 2007; Lauer et al., 2013; Pink et al., 1991). The coactivation index was calculated following Lauer et al. (2013):

$$CI = 100 \times (iEMG_{\text{antagonist}} / (iEMG_{\text{antagonist}} + iEMG_{\text{agonist}})) \quad [\text{Eq. 9}]$$

3.3.3 Existing In-Water Kinematic Data (McCabe, 2008)

The McCabe (2008) in-water kinematic data set consisted of 15 male participants of varied freestyle stroke distance specialty and competed at a national and/or international level. For in-water data collection, participants performed swimming bouts at both distance and sprint paces. The in-water kinematics were compared to the swim bench kinematics to identify differences and/or similarities and document the fidelity of the freestyle stroke simulation on the swim bench.

The 4 stroke cycles provided per participant were filtered with a 4th order, zero-lag Butterworth filter at a 4 Hz cut-off frequency, time normalized to %SC, and ensemble averaged. For comparison with the swim bench data, stroke instances were identified, and duration of phase calculated (%SC). Stroke length (m), width (m), and depth (m) peaks and ranges were extracted following the same steps outlined in section 3.4.1 (Motion Capture Processing). Elbow flexion angles at first back, shoulder-x, and end-back instances, and the ranges during the pull and push phases were calculated using Eq. 3. Shoulder roll was calculated using Eq. 1.

3.4 Statistical Analysis

The independent variables explored were the swim bench settings, rotating and fixed, and McCabe (2008) in-water data. The dependent variables consisted of the kinematic and electromyographic discrete and time-series measures extracted from the trials. Discrete measures were tested in the JMP 17 software (SAS Institute, North Carolina, USA), whereas the time-series measures were tested using open-source Statistical Parametric Mapping (SPM) and Statistical non-Parametric Mapping (SnPM) code from spm1d.org (Pataky, 2012). For all tests, an alpha of 0.05 was used.

3.4.1 Rotating vs. Fixed Bench Kinematics

The normality of the discrete measures was tested with a Shapiro-Wilk test and homogeneity of variance with a Levene's test. Differences in total shoulder roll ($^{\circ}$) between swim bench setting was tested with a Wilcoxon Signed Rank Test. Differences between right and left arms were tested using a two-way paired-samples t-test to identify if the laterality variable could be collapsed. Because laterality differences existed in, a two-way mixed ANOVA was used to compare duration (%SC) of the entry, pull, and phases, maximum stroke length (m), depth (m) and width (m), and ranges of stroke widths (m) during entry, pull, push phases, and entirety of the underwater pull between swim bench setting and laterality.

The normality of the time-series kinematic data were tested, identifying the right wrist flexion/extension angles, left wrist flexion/extension and ulnar/radial deviation angles, left elbow carry angle, shoulder roll, and hip roll as normal while the remaining measures as non-normal (Pataky et al., 2015). SPM two-way paired t-tests were used to identify differences between the rotating and fixed settings in the right wrist flexion/extension angles, left wrist flexion/extension and ulnar/radial deviation angles, left elbow carry angle, shoulder roll, and hip roll measures during a stroke cycle. Whereas SnPM two-way paired t-tests were performed to identify differences between the rotating and fixed settings in the time series measures of right and left stroke length, depth, width, 3rd distal phalanx velocity and acceleration, right wrist rotation and flexion/extension angles, left wrist rotation angles, right elbow Euler angles, left elbow flexion/extension and axial rotation, right and left shoulder Euler angles, and torso lateral flexion throughout a stroke cycle.

3.4.2 Rotating vs. Fixed Bench Muscle Activation

The normality of the co-activation indices and peak muscle activations were tested with a Shapiro Wilk test, and the homogeneity of variance with a Levene's test. The differences between swim bench setting in co-activation index for the bicep brachii-triceps brachii and the pectoralis major (clavicular, sternal, and abdominal regions)-infraspinatus pairings were tested using a two-tailed paired t-test. Due to the non-normal distributions, the differences between swim bench settings in pectoralis major (clavicular, sternal, and abdominal regions), anterior, middle, and posterior deltoids, upper and lower trapezius, serratus anterior, infraspinatus, supraspinatus, latissimus dorsi, triceps and biceps brachii peak muscle activations were tested with Wilcoxon Signed Rank Test.

The normality of the time-series sEMG data were tested and found to be non-normal. Thus SnPM was also used to compare the sEMG on the rotating versus fixed settings (Pataky et al., 2015). SnPM two-way paired t-tests were performed to identify differences between settings in the pectoralis major (clavicular, sternal, and abdominal regions), anterior, middle, and posterior deltoids, upper and lower trapezius, serratus anterior, infraspinatus, supraspinatus, latissimus dorsi, triceps and biceps brachii muscle activations throughout the stroke cycle.

3.4.3 Swim Bench vs. Existing In-Water Data (McCabe, 2008) Kinematics

Height, weight, 50 and 400 SCM freestyle time differences between the McCabe (2008) and swim bench participants were assessed using a two-way independent samples t-tests. Normality was tested with a Shapiro-Wilk test and homogeneity of variance with a Levene's test. Differences between the swim bench and McCabe (2008) in-water kinematics in phase duration, stroke length, maximum stroke depth and width at the finger, wrist, and elbow, ranges of stroke depth and width at the finger, wrist and elbow, elbow angles at the first-back, shoulder-x, and

end-back instances, the range of elbow angle during the push and pull phases, and total shoulder roll were evaluated with one-way ANOVAs. The shoulder roll angle in-water and swim bench time-series data normality was tested and was normal; thus, a SPM one-way ANOVA was used to compare the shoulder roll angles in-water versus the rotating and fixed swim bench settings throughout one stroke cycle (Pataky, 2012).

4.0 Results

This chapter presents the results for the swim bench setting and in-water comparisons. Between bench setting kinematics and electromyographic results are provided in Sections 4.1 and 4.2 respectively. Section 4.3 outlines the qualitative results for the user perception survey and the common perspectives among participants. The comparisons between the swim bench and McCabe (2008) in-water kinematics are in section 4.4.

4.1 Rotating vs Fixed Setting Kinematics

4.1.1 Phase Duration

The rotating bench setting had marginal effect on phase durations on the swim bench. No significant differences existed between settings during the entry, pull, push, or recovery phases. Regardless of setting, a main effect of laterality was observed in the entry ($p = 0.0043$) and pull ($p = 0.041$) phases. The period of entry phase on the right was 6.5 % SC compared to the 2.3 % SC on the left, whereas during the pull phase the left arm generated a longer phase duration of 30.2 % SC compared to the right arm, 27.3 % SC (Figure 19). No interaction effect existed.

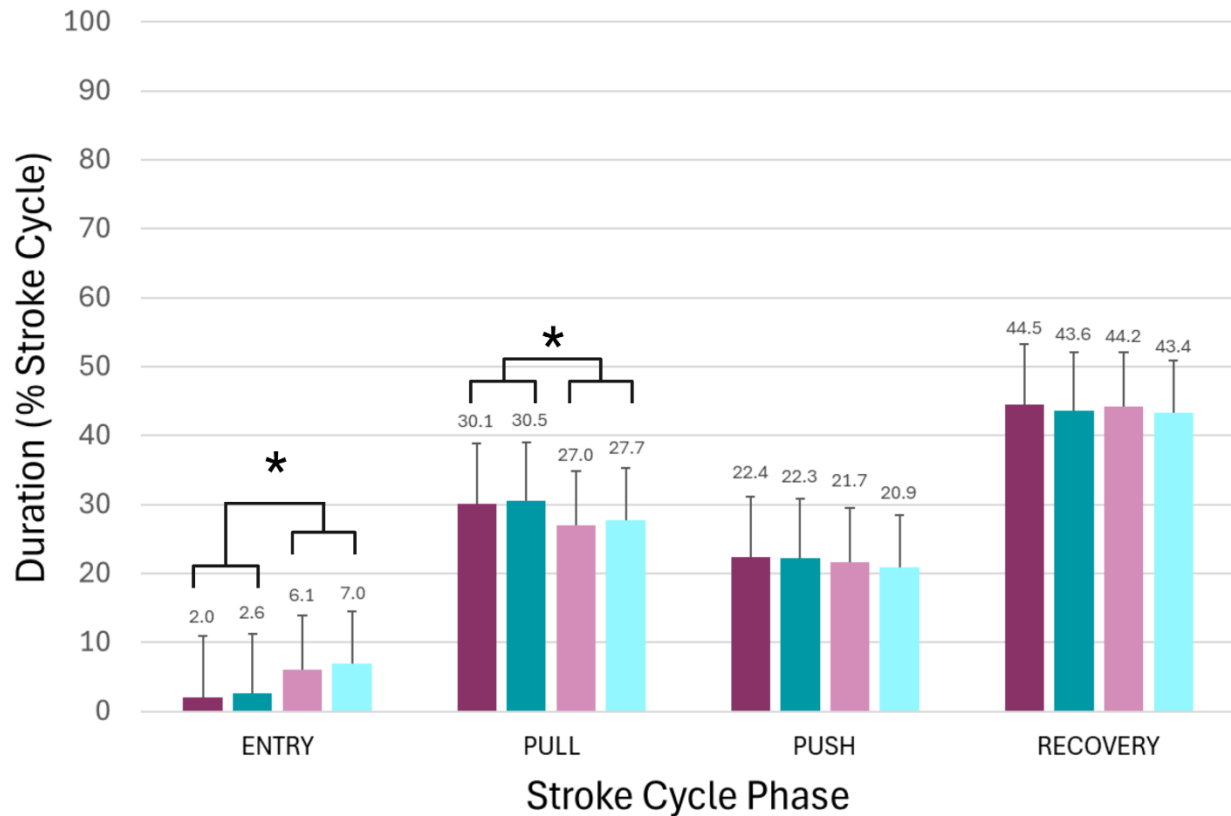


Figure 19. Right and left mean phase durations (%SC) between rotating and fixed swim bench settings. Magenta represents left side fixed setting, pink: right side fixed setting, teal: left side rotating setting, and turquoise: right side rotating setting. $p < 0.05$ indicated with an asterisk (*)

4.1.2 Stroke Characteristics

Between swim bench settings, no significant differences existed in stroke length, maximum width, or depth. Further, no differences emerged in stroke width range during the entry, pull, push phases or the underwater freestyle pull as a whole on the swim bench. A main effect of laterality was identified for maximum stroke width of the 3rd distal phalanx (Right_{rotating}: 0.28 ± 0.09 , Right_{fixed}: 0.29 ± 0.1 vs. Left_{rotating}: 0.13 ± 0.09 , Left_{fixed}: 0.13 ± 0.07 , $p < 0.0001$), where the right 3rd distal phalanx position relative to the midline was higher than the left 3rd distal phalanx (Table 11). Similarly, the range of stroke width during the entry phase was higher on the right side compared to the left (Right_{rotating}: 0.02 ± 0.03 , Right_{fixed}: 0.01 ± 0.02 vs.

Left_{rotating}: 0.01 ± 0.02 , Left_{fixed}: 0.006 ± 0.01 , $p = 0.0216$) (Table 11). For all measures, there were no interaction effects.

Table 11. Left and Right mean stroke length (m), depth (m), and width (m) measures between rotating and fixed swim bench settings. $p < 0.05$ indicated with an asterisk (*)

Measure (m)		Rotating		Fixed		Setting p-value	Laterality p-value
		Left	Right	Left	Right		
Stroke length		1.3 ± 0.02	1.3 ± 0.02	1.3 ± 0.02	1.3 ± 0.02	0.7871	0.5238
Stroke width	Maximum	0.13 ± 0.09	0.28 ± 0.09	0.13 ± 0.07	0.29 ± 0.1	0.9473	< 0.0001*
	Underwater range	0.15 ± 0.05	0.17 ± 0.05	0.15 ± 0.02	0.17 ± 0.05	0.9659	0.1168
	Entry range	0.01 ± 0.02	0.02 ± 0.03	0.006 ± 0.01	0.01 ± 0.02	0.5252	0.0216*
	Pull range	0.1 ± 0.04	0.09 ± 0.04	0.09 ± 0.04	0.08 ± 0.05	0.8163	0.2288
	Push Range	0.08 ± 0.03	0.08 ± 0.03	0.08 ± 0.04	0.09 ± 0.04	0.6868	0.5572
Stroke depth: maximum		0.49 ± 0.09	0.48 ± 0.09	0.46 ± 0.07	0.45 ± 0.11	0.3102	0.6611

4.1.3 Third Distal Phalanx Translational Velocity and Acceleration

The right and left third distal phalanx translational velocities and accelerations on the rotating setting did not differ from the fixed in the anteroposterior (x), vertical (y) and mediolateral (z) directions (Figure 20). Yet, the left third distal phalanx anteroposterior acceleration briefly approached significance in the x direction about the 50 % SC time point, with more deceleration on the rotating setting compared to the fixed nearing the end-back instance (Figure 21).

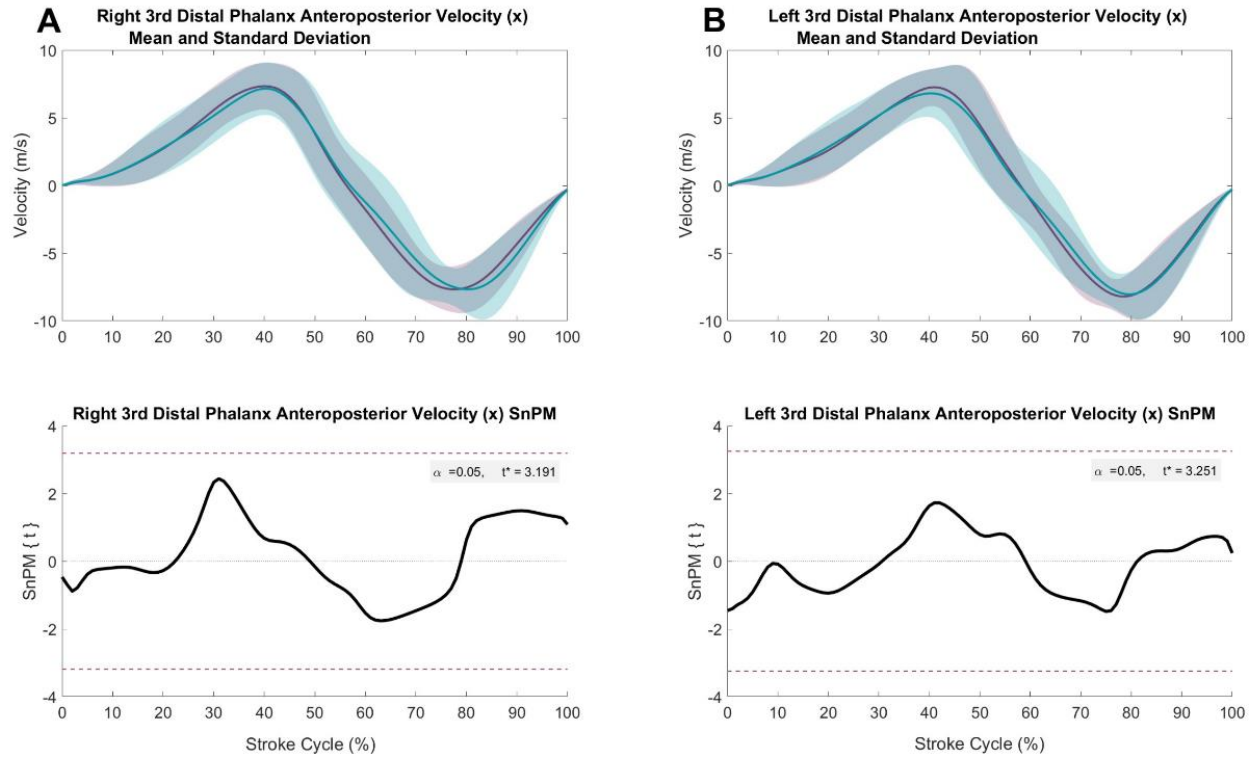


Figure 20. Between rotating and fixed setting, A) right and B) left time-series 3rd distal phalanx (DP3) anteroposterior velocity (m/s) mean and standard deviation (above) and SnPM (below). Teal line and error cloud represents the rotating setting, the purple line and error cloud: fixed, and purple dotted line: the critical t-score.

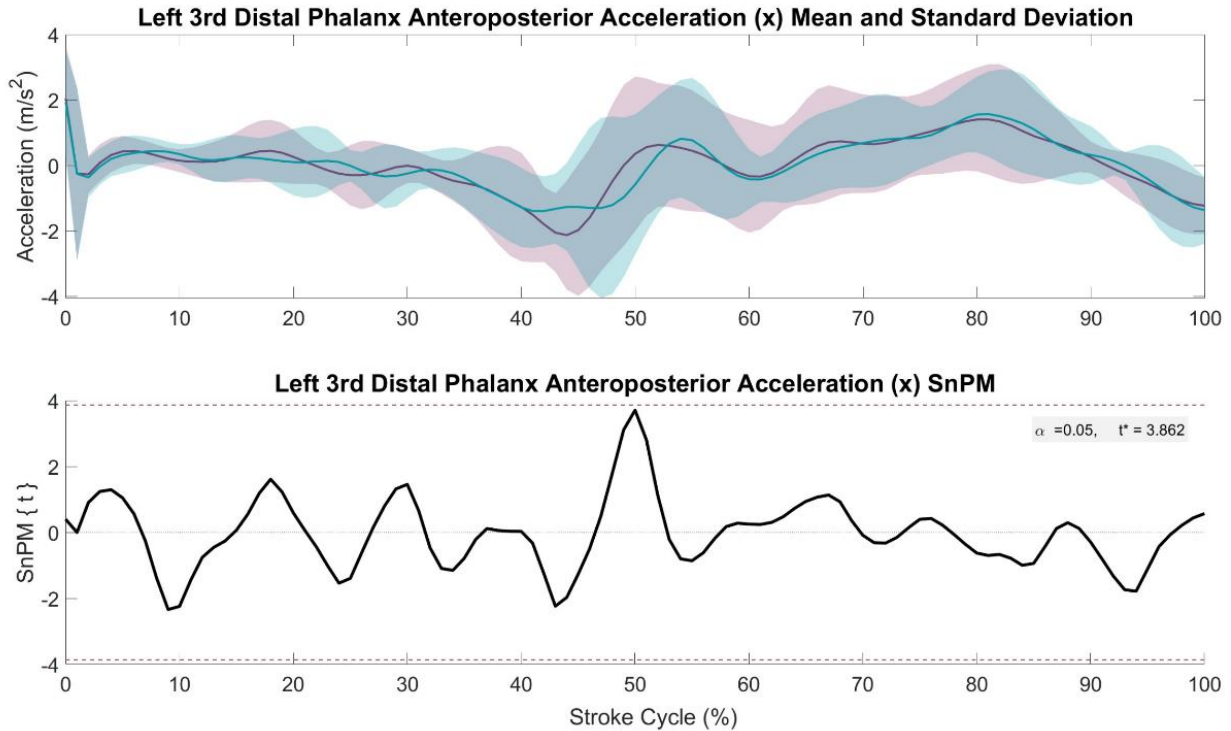


Figure 21. Between rotating and fixed setting left time-series 3rd distal phalanx (DP3) anteroposterior acceleration (m/s²) mean and standard deviation (above) and SnPM (below). Teal line and error cloud represents the rotating setting, the purple line and error cloud: fixed, and purple dotted line: the critical t-score.

4.1.4 Joint Angles

All right shoulder Euler angles, and the left horizontal flexion and axial rotation angles did not significantly differ. Yet, the left shoulder axial rotation approached significance at 46 – 48 % SC, nearing end-back, with higher internal rotation on the rotating setting compared to the fixed (Figure 22b). The rotating setting also produced more left shoulder elevation at 56.6 – 62.2 % SC ($p = 0.08$), during the transition between the push and recovery phases about the end-back instance (Figure 22a). In all elbow Euler angles, no differences existed between settings. Additionally, both right and left wrist flexion/extension and rotation and left ulnar/radial deviation angles did not differ (Figures 23a, b, d). During the recovery phase of the stroke, a difference existed in the right ulnar/radial deviation angles. At 72.4 – 80.4 % SC, the fixed

setting produced higher radial deviation, while the right wrist on the rotating setting was closer to neutral ($p = 0.024$) (Figure 24c).

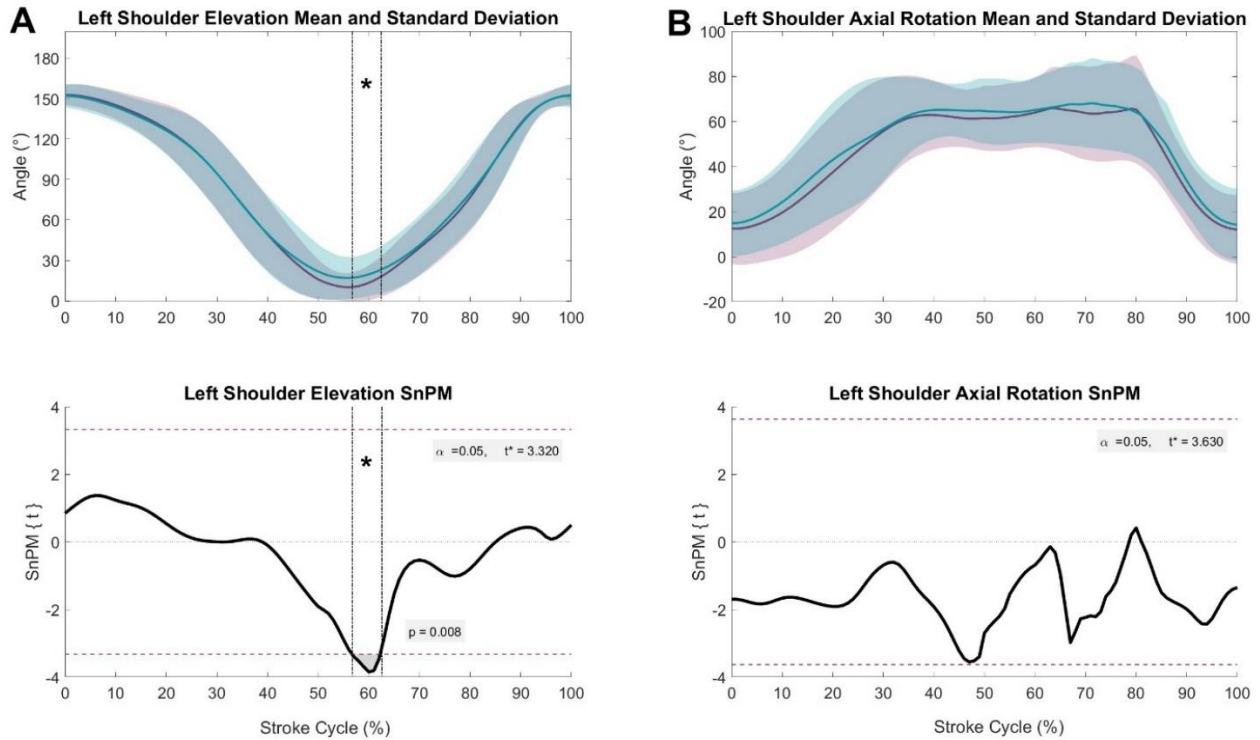


Figure 22. Between rotating and fixed setting, A) left time-series shoulder elevation angles mean and standard deviation (above) and SnPM (below) and B) left time-series shoulder axial rotation angles mean and standard deviation (above) and SnPM (below). Flexion in the positive direction, 0° is neutral, and extension in the negative direction. Internal rotation in the positive direction, 0° is neutral, and external rotation in the negative direction. Teal line and error cloud represents the rotating setting, the purple line and error cloud: fixed, and purple dotted lines: the critical t-score. The portion of SnPM data that crosses the t-score threshold is significant, $p < 0.05$, and indicated as a shaded grey area and with an asterisk (*).

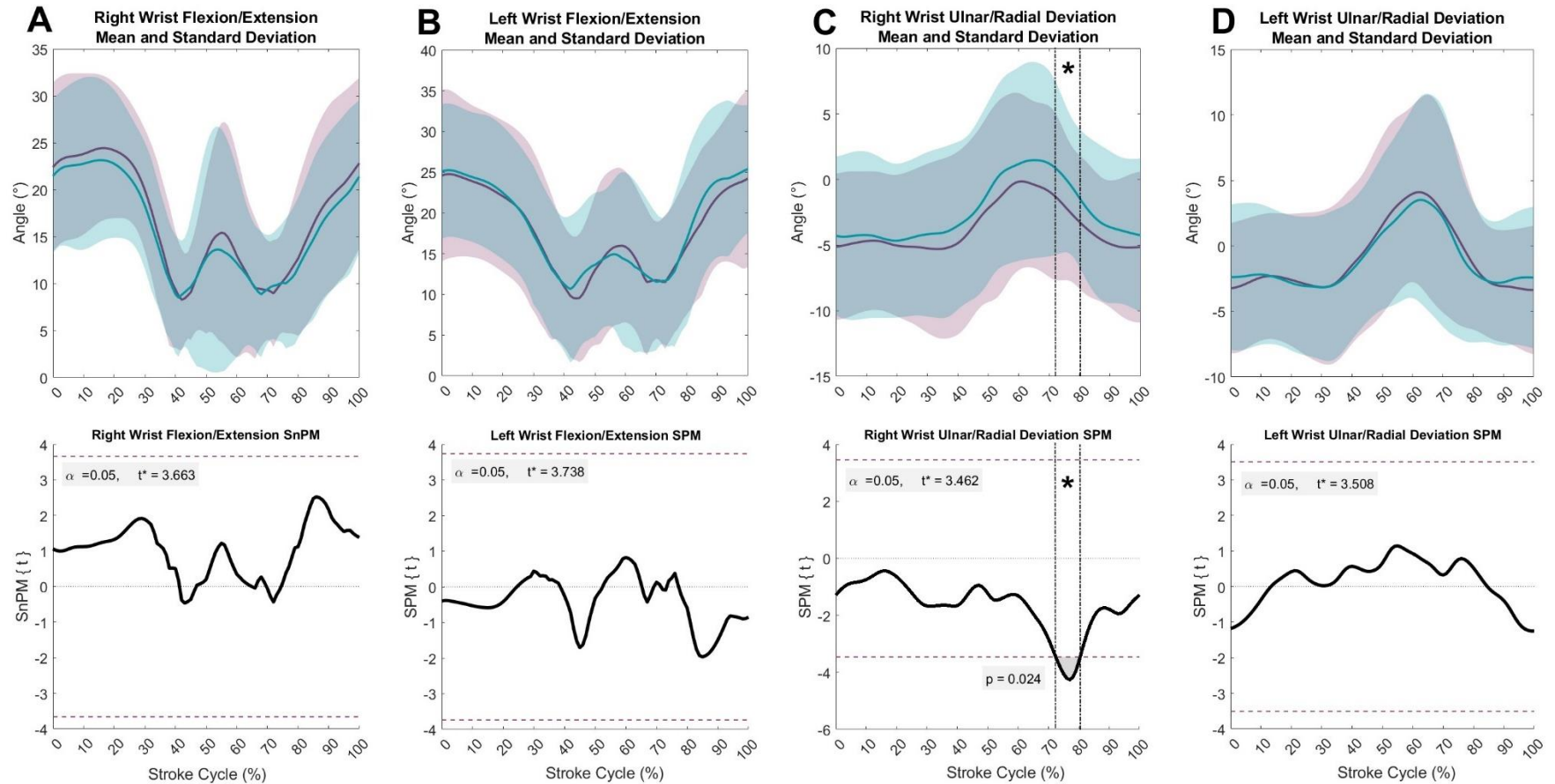


Figure 23. Between rotating and fixed setting A) right time-series wrist flexion/extension angles mean and standard deviation (above) and SnPM (below), B) left time-series wrist flexion/extension angles mean and standard deviation (above) and SPM (below), C) right time-series wrist ulnar and radial deviation angles mean and standard deviation (above) and SPM (below), and D) left time-series wrist ulnar and radial deviation angles mean and standard deviation (above) and SPM (below). Flexion in the positive direction, 0° is neutral, and extension in the negative direction. Ulnar deviation in the positive direction, 0° is neutral, and radial deviation in the negative direction. Teal line and error cloud represents the rotating setting, the purple line and error cloud: fixed, and purple dotted lines: the critical t-score. The portion of SnPM or SPM data that crosses the t-score threshold is significant, $p < 0.05$, and indicated as a shaded grey area and with an asterisk (*)

4.1.5 Shoulder Roll, Hip Roll, and Torso Lateral Flexion

Shoulder roll did not differ between settings, with the movement pattern following closely together, producing similar total and peak shoulder roll angles (Figure 24a). The hips were stationary at 10-11° on both settings, with negligible roll occurring, or differences identified. Although, an introduction of lateral torso flexion in opposition to the shoulder roll was introduced on both settings (Figure 24b).

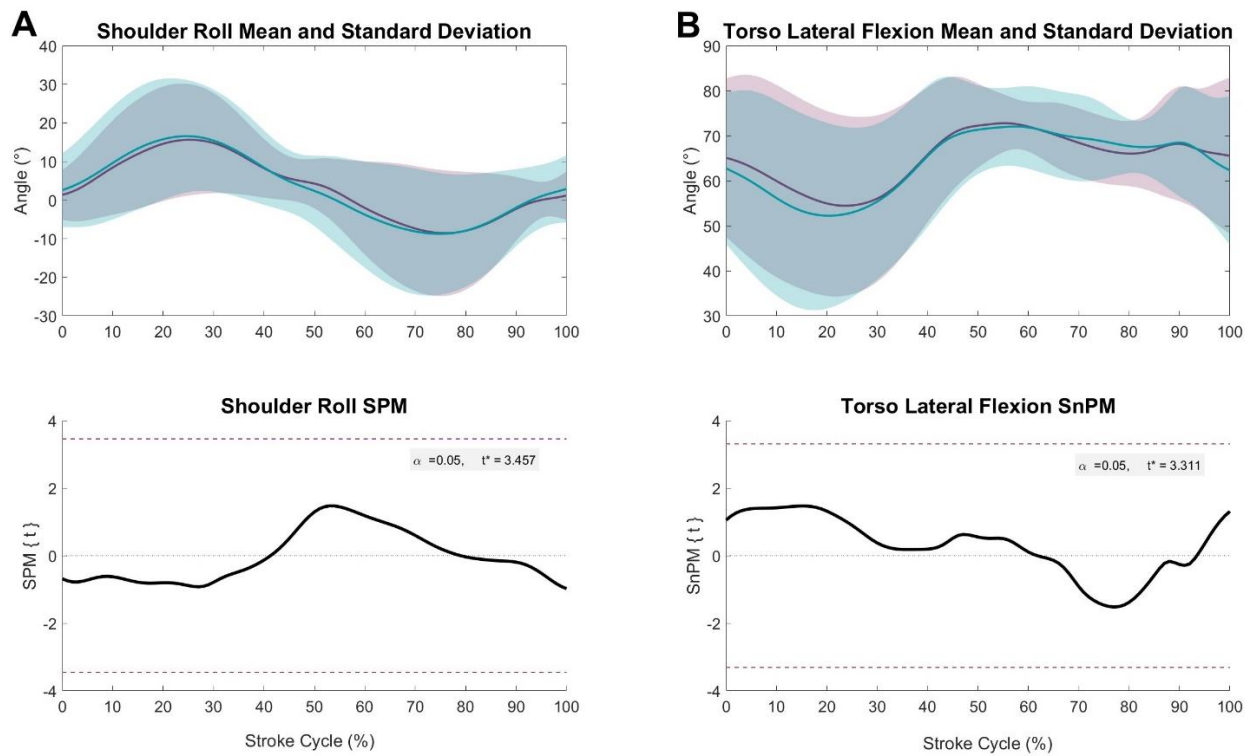


Figure 24. Between rotating and fixed setting, A) time-series shoulder roll mean and standard deviation (above) and associated SPM (below) and B) time-series lateral torso flexion mean and standard deviation (above) and associated SnPM (below). Rightward in the positive direction and leftward in the negative direction. Teal line and error cloud represents the rotating setting, the purple line and error cloud: fixed, and purple dotted lines: the critical t-score.

4.2 Rotating vs. Fixed Setting Muscle Activity

4.2.1 Peak Activations and Co-activation Indices

No differences existed between the mean peak muscle activations (Table 12).

Additionally, none of the bicep-triceps brachii or pectoralis major (clavicular, sternal, abdominal regions)-infraspinatus co-activation indices differed (Figure 25).

Table 12. Mean peak muscle activations (% MVIC) between rotating and fixed swim bench settings. $p < 0.05$ indicated with an asterisk (*)

Muscle		Rotating	Fixed	p-value
Pectoralis Major	Clavicular	5 ± 4	7 ± 7	0.578
	Sternal	8 ± 7	9 ± 12	0.8057
	Abdominal	27 ± 21	27 ± 22	0.9843
Deltoid	Anterior	10 ± 8	12 ± 10	0.665
	Middle	33 ± 11	33 ± 11	0.9237
	Posterior	29 ± 8	30 ± 9	0.6648
Latissimus Dorsi		39 ± 22	40 ± 21	0.9665
Biceps Brachii		6 ± 4	6 ± 4	0.9165
Triceps Brachii		28 ± 13	32 ± 17	0.6329
Trapezius	Upper	28 ± 22	30 ± 28	0.8517
	Lower	23 ± 8	23 ± 7	0.884
Serratus Anterior		27 ± 16	25 ± 14	0.7199
Infraspinatus		16 ± 7	16 ± 5	0.8486
Supraspinatus		23 ± 10	23 ± 13	0.8979

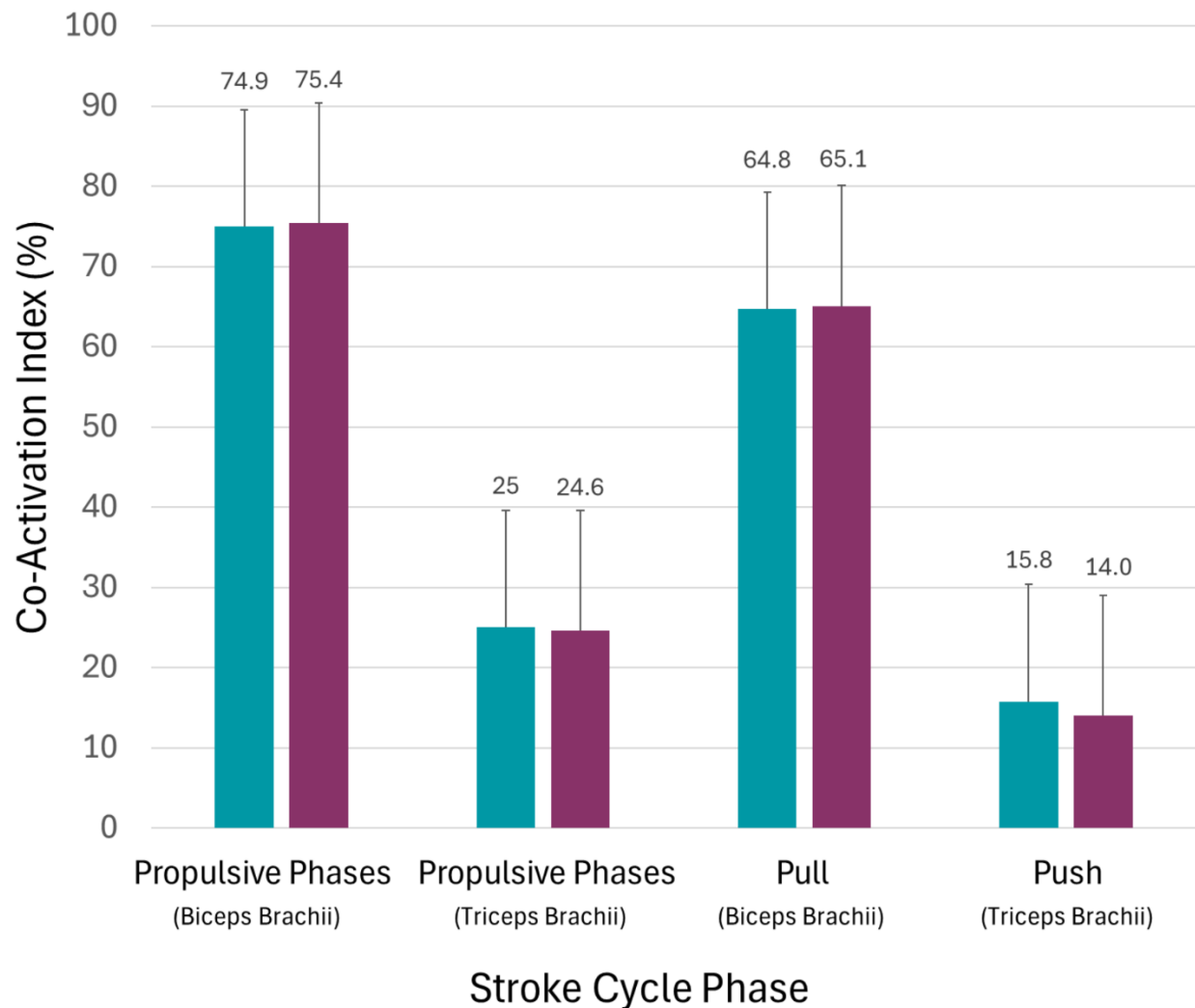


Figure 25. Between rotating and fixed setting mean biceps brachii-triceps brachii co-activation indices throughout the propulsive phases, pull phase, and push phase. Teal represents the rotating setting and purple: the fixed.

4.2.2 Time-Series Muscle Activation

With the exception of infraspinatus, few differences existed in the muscle activation patterns between swim bench settings. The fixed setting produced a higher infraspinatus activation, $p = 0.014$, 33.4 – 38.7 % SC, during the pull phase compared to the rotating bench (Figure 26). Despite the lack of significance, the rotating bench produced lower muscle activations in all regions of the pectoralis major, triceps brachii, biceps brachii, and posterior

deltoid and more gradual slopes in the pectoralis major, biceps brachii, middle and posterior deltoids, and supraspinatus (Figure 27).

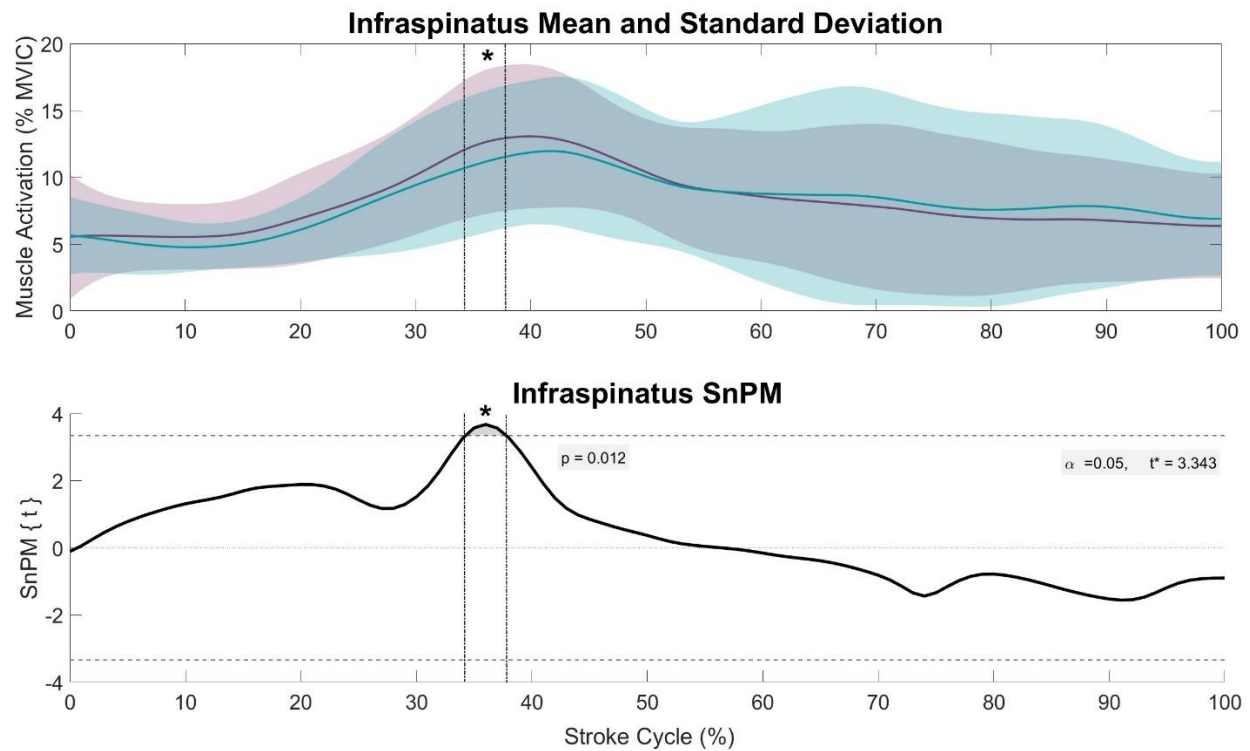


Figure 26. Between rotating and fixed setting time-series infraspinatus muscle activations mean and standard deviation (above) and associated SnPM (below). Teal line and error cloud represents the rotating setting, the purple line and error cloud: fixed, and purple dotted line: the critical t-score. The portion of SnPM data that crosses the t-score threshold is significant, $p < 0.05$, and indicated as a shaded grey area and with an asterisk (*).

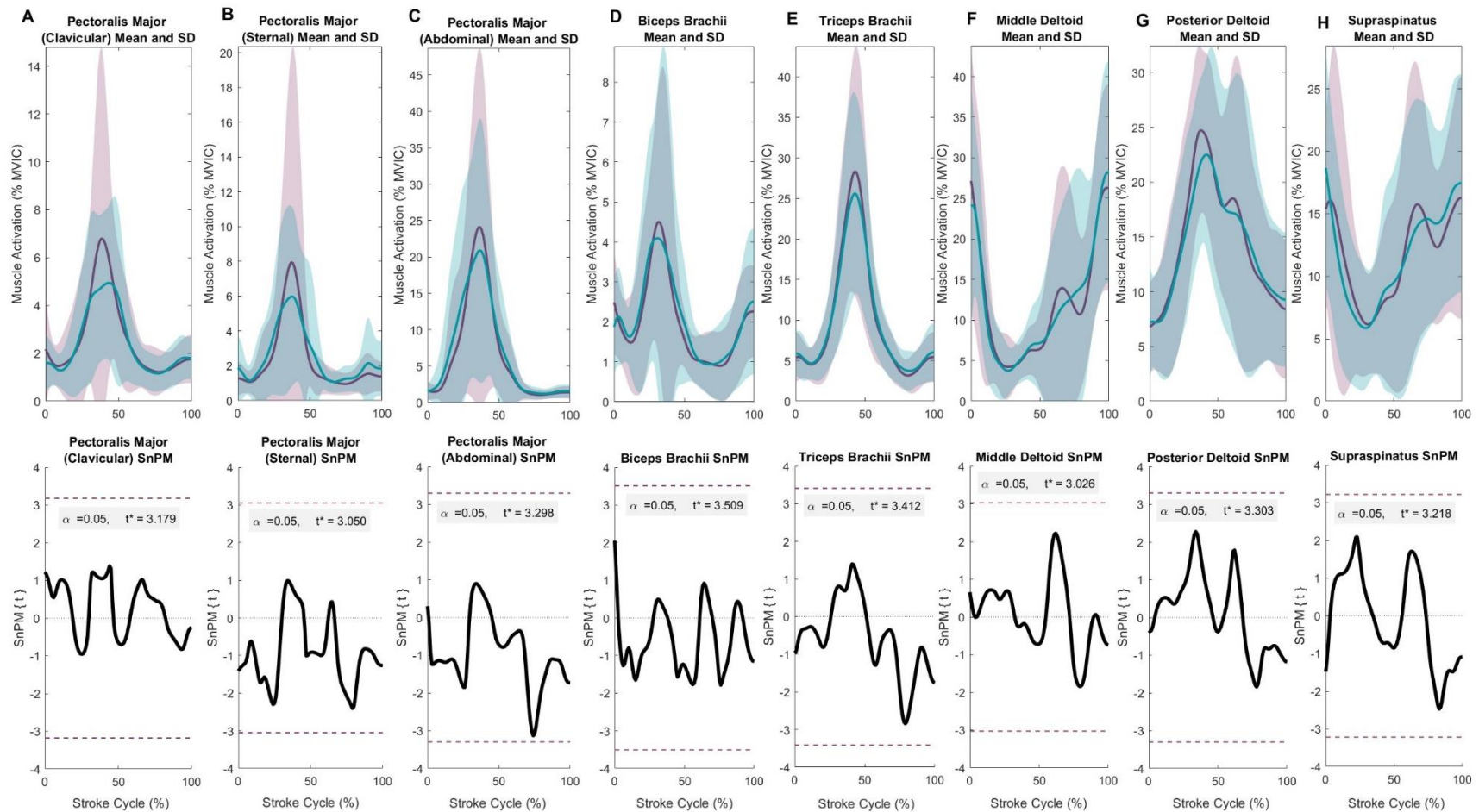


Figure 27. Between rotating and fixed setting, time-series pectoralis major A) Clavicular, B) Sternal, and C) Abdominal regions, D) triceps brachii, E) biceps brachii, F) middle deltoid, G) posterior deltoid, and H) supraspinatus muscle activation means and standard deviations (above) and associated SnPM (below). Teal line and error cloud represents the rotating setting, the purple line and error cloud: fixed, and purple dotted line: the critical t-score.

4.3 Rating of Perceived Exertion

No significant changes occurred in RPE on the modified borg scale across all trials and between settings (Figure 17) (Borg, 1998). Swimmers achieved a mean RPE of 2.3 ± 1.3 on the rotating setting and 2.3 ± 1.0 on the fixed.

4.4 Swim Bench User Perception Survey

4.4.1 Swim bench user history

60 % of participants used a swim bench prior to the study for circuit training, freestyle swimming technique adjustments, and training during COVID-19 pool shutdowns. 75 % of past users felt the swim bench met the intended use.

4.4.2 Perspectives

Participants indicated that the rotating setting did not rotate enough to feel a difference and they rotate more in-water than on the bench. The “natural twist in response to the pull was not quite there on the bench” and it was “harder to mimic the roll because of gravity”. Despite this, the participants would still use the bench and felt it was similar enough to swimming.

4.4.3 Preferred setting

46.6 % of participants preferred the rotating setting, whereas 40 % preferred the fixed and 13.3 % did not prefer either setting. Participants felt the fixed setting was easier and the rotating setting was unstable, requiring more core engagement.

4.4.4 Similarity to in-water technique

73.3 % of the participants indicated the rotating bench setting felt closest to their in-water technique, whereas 20 % aligned with the fixed setting and 6.6 % felt neither replicated their in-

water stroke. Participants commented that the rotating setting was not as natural as in-water but was needed. Further, straight-arm freestyle swimming technique users felt they could not replicate the in-water feeling when all the resistance is at the hand and missing along the forearm or arm.

4.4.5 Resistance compared to water

26.6 % of participants disagreed, and 13.3 % strongly disagreed that the resistance on the swim bench felt similar to water, however 26.6 % of the participants agreed and 33.3 % were neutral. Participants described the level and consistency of force different to water, with an uneven resistance that was higher at start up during the catch and little afterwards. Additionally, participants identified difficulties maintaining their in-water technique on the swim bench, where it was “harder to keep a high catch due to the lack of water resistance”.

4.4.6 Would they use the swim bench if provided?

The majority of participants responded favourably to using the swim bench as a resource. 33.3 % strongly agreed, 26.6 % agree, 20 % neutral, 6.6 % disagree, and 13.3 % strongly disagreed. Participants would not use the swim bench to replace in-water training, but to work along side it for swimming technique adjustments and circuit training.

4.5 Swim Bench vs. Existing In-Water Data (McCabe, 2008)

4.5.1 Phase Durations

All phase durations differed significantly between the in-water data and the swim bench (Figure 28). The entry phase during in-water swimming was longer than the simulated version on the swim bench (rotating: 3.8 % SC, fixed: 4.8 % SC, in-water: 35.2 % SC, $p < 0.0001$), yet the pull (rotating: 29.3 % SC, fixed: 29.1 % SC, in-water: 18.2 % SC, $p < 0.0001$), push (rotating:

21.7 % SC, fixed: 21.6 % SC, in-water: 17 % SC, $p < 0.0001$), and recovery (rotating: 44.3 % SC, fixed: 43.5 % SC, in-water: 29.5 % SC, $p < 0.0001$) phase durations on the swim bench were longer than for the in-water freestyle stroke.

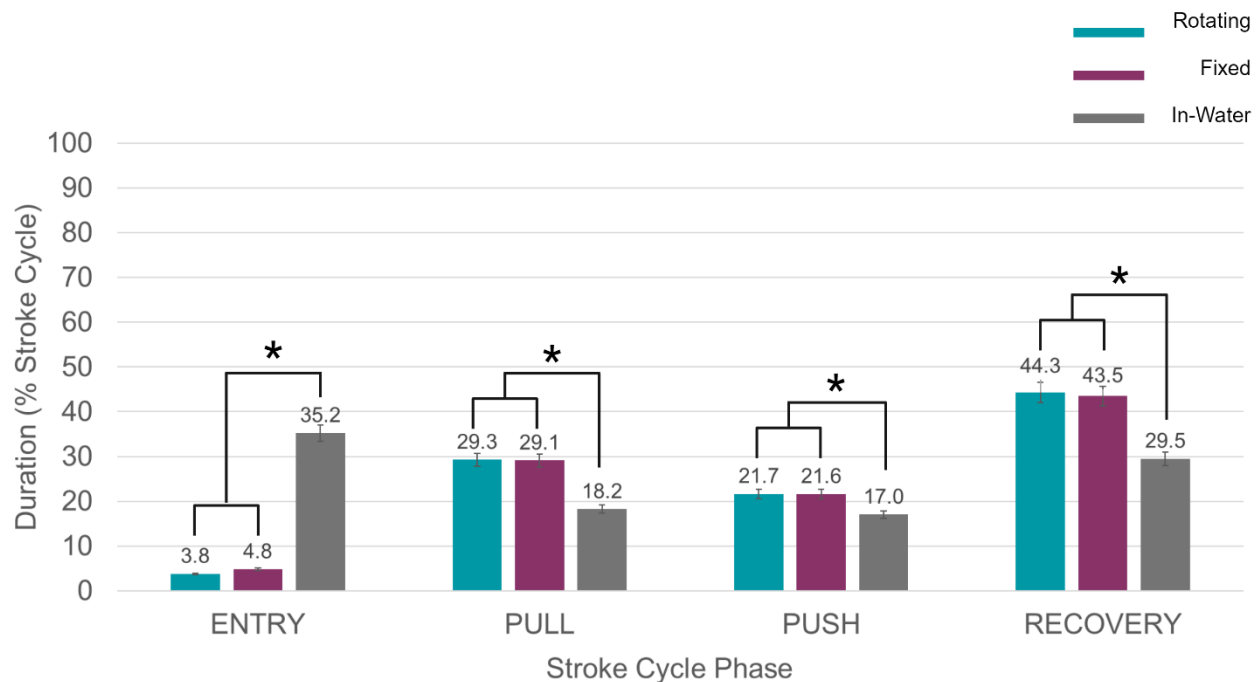


Figure 28. Mean phase durations (%SC) between in-water freestyle swimming and swim bench settings. Teal represents the rotating setting, purple: fixed, and grey: in-water swimming. $p < 0.05$ indicated with an asterisk (*)

4.5.2 Stroke Characteristics

The mean stroke length was greater during in-water freestyle swimming compared to the swim bench settings and the swim bench is only achieved 59% of the in-water swimming length (Table 13). The mean peak stroke widths were narrower on the swim bench compared to in-water at the third distal phalanx (33% comparative decrease compared to in-water), wrist (26% reduction), and the elbow (rotating: 14% and fixed: 15% reductions) (Table 12, Figure 29a). Additionally, the mean stroke width ranges throughout the stroke cycle were less on the swim bench settings at all 3 locations, with percent differences of the in-water stroke width ranges at

41, 40, and 35% on the rotating setting and 40, 38, and 30% on the fixed respectively (Table 12, Figure 29b). Similarly, the stroke depth ranges at the third distal phalanx, wrist, and elbow were reduced on the swim bench (decrease of rotating: 28%, 30%, and 32% fixed: 24%, 26%, 26% comparatively to the in-water stroke depth ranges respectively) (Table 13, Figure 30b). The mean peak depths were greater during in-water swimming at the wrist (rotating 30%, fixed 26% reduction from in-water depth) and elbow (rotating: 32% and fixed: 26% reduction from in-water depth), yet no difference existed between the swim bench and in-water third distal phalanx mean peak stroke depth (Table 13, Figure 30a).

Table 13. Mean stroke length, depth, and width (m) measures between the in-water freestyle swimming and swim bench settings. $p < 0.05$ indicated with an asterisk (*)

Measure (m)		In-water	Rotating	Fixed	p-value
Stroke length		2.2 ± 1.0^A	1.3 ± 0.12^B	1.3 ± 0.14^B	0.0002*
Stroke width	DP3 peak	0.31 ± 0.07^A	0.21 ± 0.03^B	0.21 ± 0.03^B	<0.0001*
	Wrist peak	0.30 ± 0.06^A	0.22 ± 0.02^B	0.22 ± 0.02^B	<0.0001*
	Elbow peak	0.31 ± 0.04^A	0.27 ± 0.02^B	0.26 ± 0.03^B	<0.0001*
	DP3 range	0.27 ± 0.07^A	0.15 ± 0.02^B	0.16 ± 0.04^B	<0.0001*
	Wrist range	0.23 ± 0.06^A	0.13 ± 0.02^B	0.14 ± 0.03^B	0.0003*
	Elbow range	0.21 ± 0.04^A	0.13 ± 0.03^B	0.14 ± 0.03^B	<0.0001*
Stroke depth	DP3 peak	0.71 ± 0.04	0.69 ± 0.06^B	0.70 ± 0.06^B	0.69
	Wrist peak	0.58 ± 0.05^A	0.53 ± 0.05^B	0.54 ± 0.05^B	0.0271*
	Elbow peak	0.39 ± 0.05^A	0.32 ± 0.04^B	0.32 ± 0.04^B	0.0002*
	DP3 range	0.64 ± 0.05^A	0.46 ± 0.07^B	0.48 ± 0.10^B	<0.0001*
	Wrist range	0.56 ± 0.06^A	0.39 ± 0.05^B	0.41 ± 0.07^B	0.0002*
	Elbow range	0.38 ± 0.05^A	0.26 ± 0.06^B	0.28 ± 0.08^B	<0.0001*

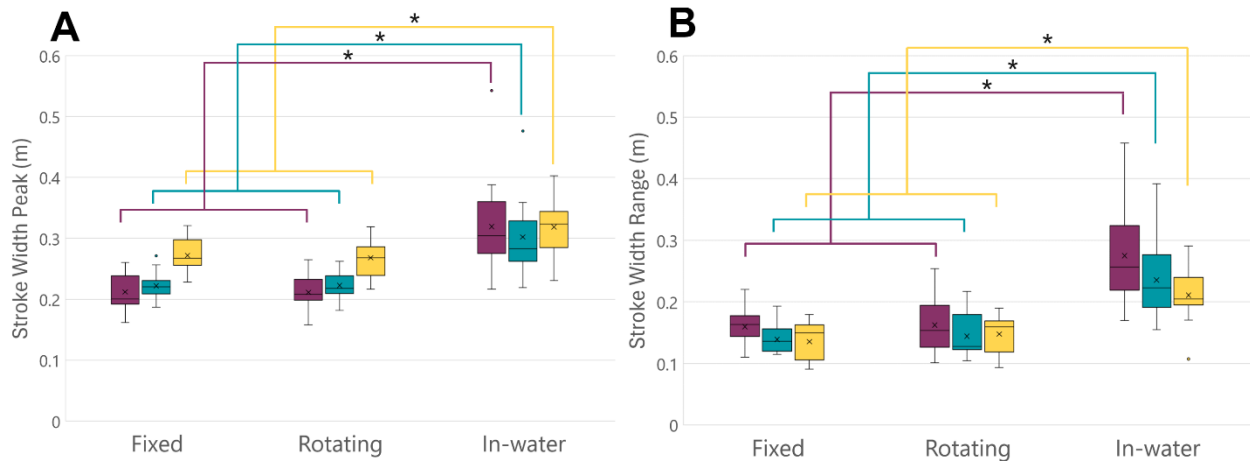


Figure 29. Stroke width (m) between in-water freestyle swimming and swim bench settings. A) The mean peak stroke width (m) during the underwater pull B) the range of stroke width (m) during the underwater pull. Purple represents the 3rd distal phalanx, teal: the wrist, and yellow: the elbow. $p < 0.05$ indicated by an asterisk (*)

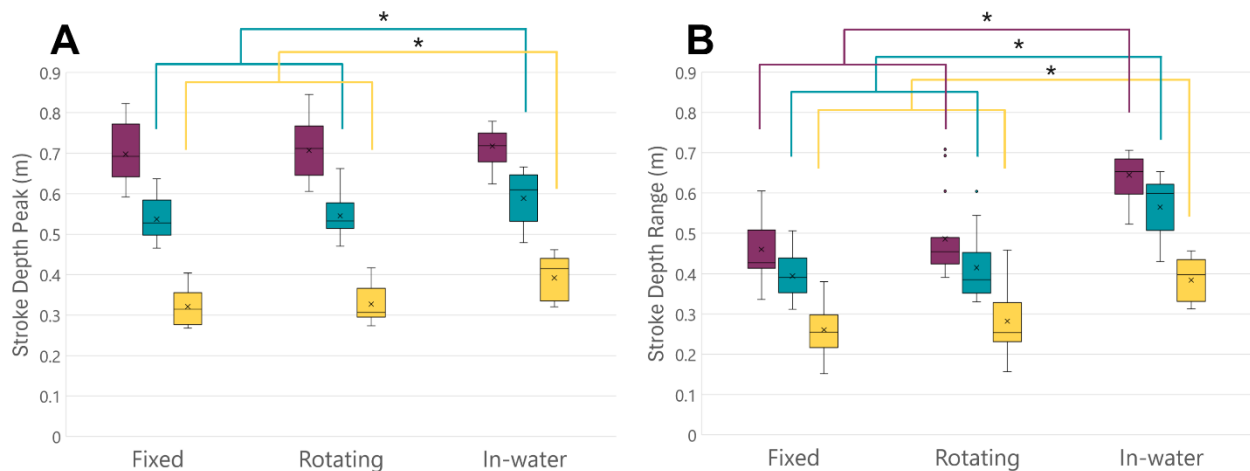


Figure 30. Stroke depth (m) between in-water freestyle swimming and swim bench settings. A) The mean peak stroke depth (m) during the underwater pull B) the range of stroke depth (m) during the underwater pull. Purple represents the 3rd distal phalanx, teal: the wrist, and yellow: the elbow. $p < 0.05$ indicated by an asterisk (*).

4.5.3 Third Distal Phalanx Translational Velocity and Acceleration

The mean, absolute, peak velocities and accelerations generated on the swim bench were consistently higher than in-water swimming in each direction during both the pull and push phases. The anteroposterior velocities during both phases in-water is 85% less compared to the

velocity produced on the swim bench (Table 14, Figure 31). Similarly, the vertical and mediolateral velocities in-water are less than observed on the swim bench (vertical pull: 65% comparative reduction, vertical push: 62%, mediolateral pull: 32%, and mediolateral push: 59%) (Table 14, Figure 31). The accelerations followed a similar pattern, yet the in-water swimming, comparatively, represented 4% of the swim bench accelerations during the pull phase in each direction, and 6% of the anteroposterior, 10% of the vertical, and 9% of the mediolateral swim bench accelerations (Table 14, Figure 32).

Table 14. Third distal phalanx mean absolute peak velocity (m/s) and acceleration (m/s²) between in-water freestyle swimming and swim bench settings during the pull and push phases. *p* < 0.05 indicated with an asterisk (*)

Measure	Phase	Direction	In-water	Rotating	Fixed	p-value
Velocity (m/s)	Pull	Anteroposterior	1 ± 0.18	6.7 ± 1.3	6.6 ± 1.4	<0.0001*
		Vertical	1 ± 0.16	3.1 ± 0.75	3 ± 0.9	<0.0001*
		Mediolateral	0.73 ± 0.41	1 ± 0.36	1 ± 0.33	0.0261*
	Push	Anteroposterior	1.2 ± 0.3	7.9 ± 1.3	8 ± 1.4	<0.0001*
		Vertical	2 ± 0.39	5.4 ± 1.3	5.3 ± 1.3	<0.0001*
		Mediolateral	0.61 ± 0.33	1.5 ± 0.85	1.5 ± 0.72	0.0008*
Acceleration (m/s ²)	Pull	Anteroposterior	0.06 ± 0.02	1.5 ± 0.46	1.7 ± 0.86	<0.0001*
		Vertical	0.44 ± 0.37	10 ± 8.3	11 ± 6.9	<0.0001*
		Mediolateral	0.17 ± 0.17	4.9 ± 4.5	4.4 ± 3.3	0.0004*
	Push	Anteroposterior	0.17 ± 0.12	3.3 ± 1.1	3.3 ± 0.98	<0.0001*
		Vertical	0.4 ± 0.4	4.3 ± 2	4.4 ± 2.2	<0.0001*
		Mediolateral	0.16 ± 0.14	2 ± 1	2 ± 1.3	<0.0001*

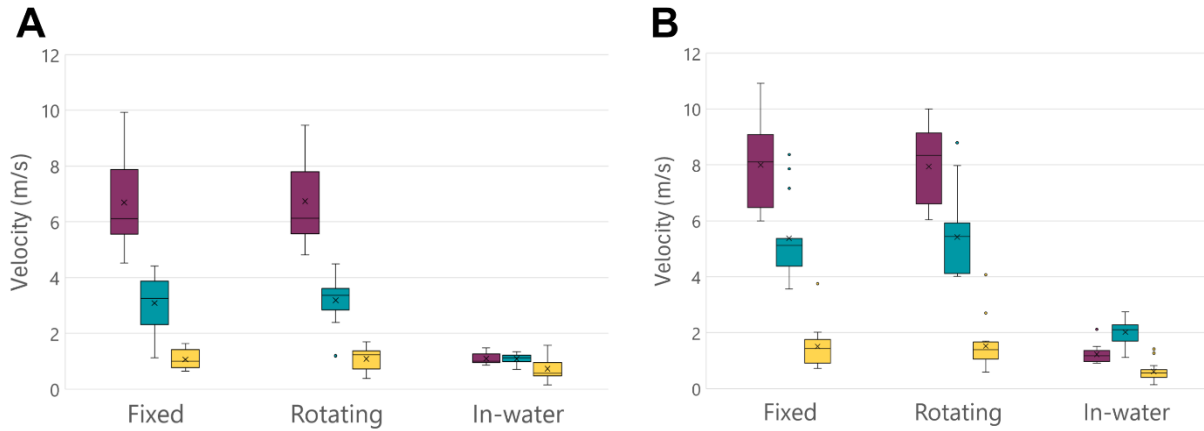


Figure 31. Third distal phalanx velocity (m/s) between in-water swimming and swim bench settings during the A) pull phase and B) push phase. Purple represents the anteroposterior direction, teal: the vertical, and yellow: the mediolateral. $p < 0.05$ indicated by an asterisk (*).

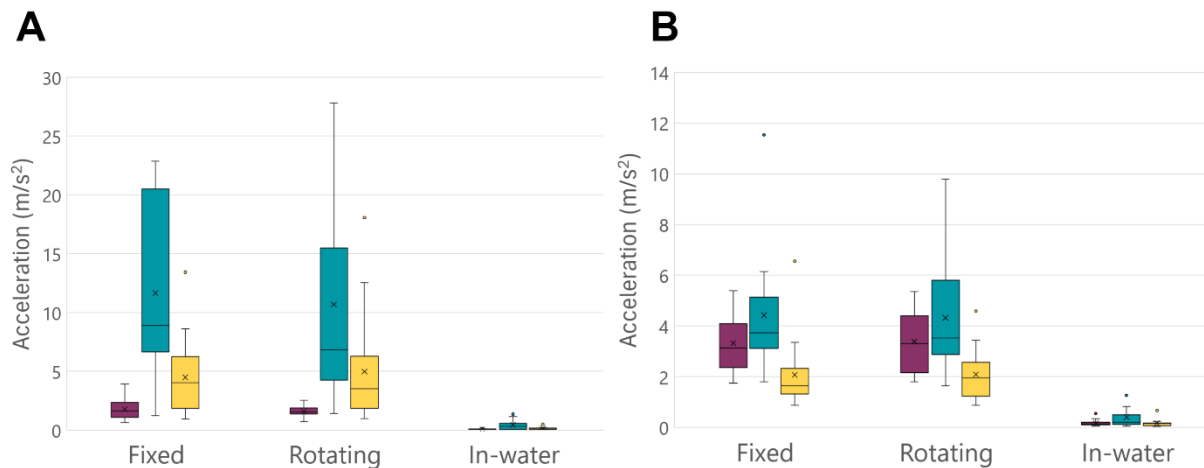


Figure 32. Third distal phalanx acceleration (m/s^2) between in-water swimming and swim bench settings during the A) pull phase and B) push phase. Purple represents the anteroposterior direction, teal: the vertical, and yellow: the mediolateral. $p < 0.05$ indicated by an asterisk (*).

4.5.4 Elbow angle

No differences existed between the in-water and swim bench elbow flexion angles at the first-back, shoulder-x, or end-back instances. Further, the elbow flexion angle ranges during the pull and push phases did not differ between the data sets (Table 14).

Table 15. Mean elbow flexion/extension angles (°) between in-water freestyle swimming and swim bench settings at the first-back, shoulder-x, and end-back instances and the mean ranges during the pull and push phases. $p < 0.05$ indicated with an asterisk (*)

Elbow flexion/extension (°)	In-water	Rotating	Fixed	p-value
First-back	151 ± 8.7	146 ± 7.3	145 ± 7.0	0.1462
Shoulder-x	106 ± 8	107 ± 11	108 ± 13	0.9116
End-back	142 ± 8.6	140 ± 13	141 ± 13	0.8468
Pull range	45.1 ± 7.3	39.9 ± 12	38.9 ± 13	0.2901
Push range	39.3 ± 9.6	38.8 ± 15	39.9 ± 14	0.9725

4.5.5 Shoulder Roll

Peak and total shoulder roll magnitude angles were significantly higher during in-water swimming compared to the simulated swimming on the swim bench (Table 15). The extent of shoulder roll angle throughout a stroke cycle was higher during in-water swimming between 0 – 1 % SC ($p = 0.049$), 14 – 49 % SC ($p < 0.001$), and 59 – 99.8 % SC ($p < 0.001$) as well (Figure 33).

Table 16. Mean peak and total shoulder roll angle (°) between in-water freestyle swimming and swim bench settings. $p < 0.05$ indicated with an asterisk (*)

Shoulder Roll (°)	In-water	Rotating	Fixed	p-value
Peak	50.2 ± 3.9 ^A	22 ± 14.7 ^B	19.6 ± 12.8 ^B	<0.0001*
Total magnitude	96.4 ± 7 ^A	36.6 ± 28.5 ^B	33 ± 26.3 ^B	<0.0001*

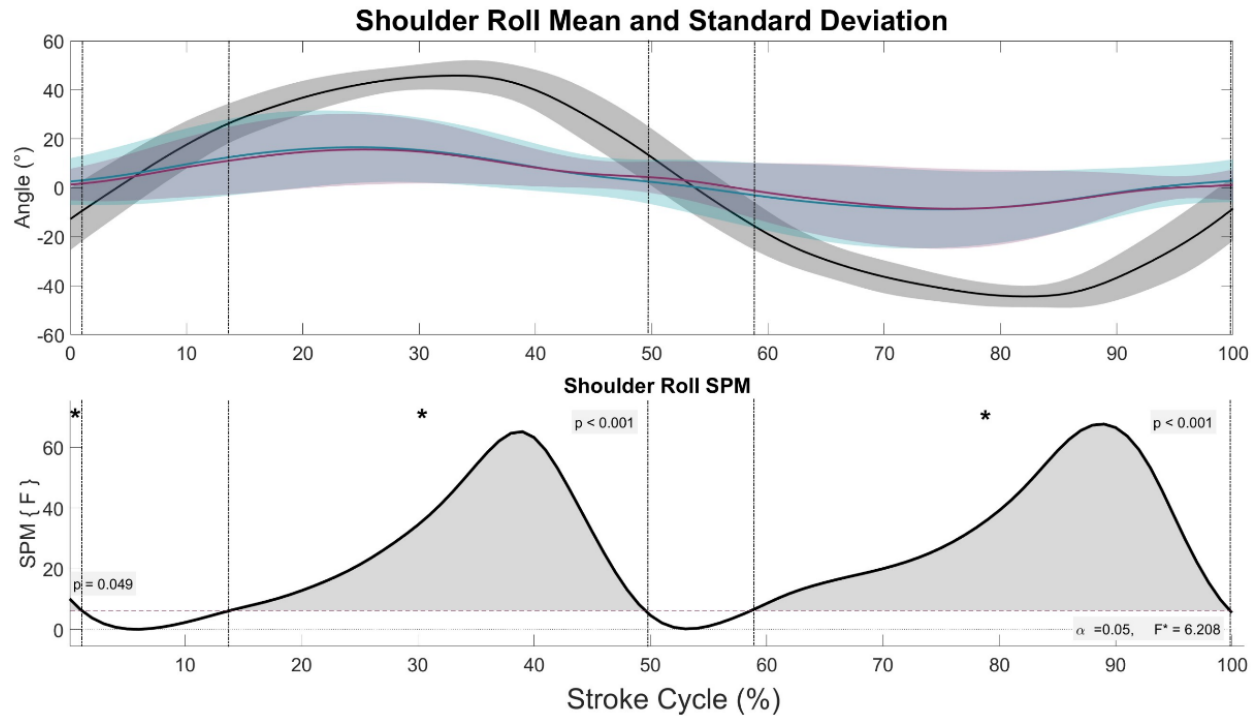


Figure 33. Between in-water freestyle swimming and swim bench setting time series shoulder roll angles during a stroke cycle. Shoulder roll angle mean and standard deviation (above) and associated SPM (below). In the mean and standard deviation chart, the teal line and error cloud represents the rotating setting, the purple line and error cloud: fixed, the black line and grey error cloud: in-water swimming. In the SPM chart the purple dotted line represents the critical t-score and the portion of SPM data that crosses the t-score threshold is significant, $p < 0.05$, indicated as a shaded grey area and with an asterisk (*).

5.0 Discussion

The purpose of this thesis was to assess the influence of swim bench setting on freestyle stroke kinematics and muscle activations and evaluate the similarities between the swim bench and pre-existing in-water kinematic data from McCabe (2008). Overall, the rotating setting did not substantially alter the kinematic or muscle activation patterns compared to the fixed, and the swim bench movement patterns differ from in-water swimming. This chapter revisits the hypotheses stated in the introduction (Section 5.1), connects the to the current literature (Sections 5.2 & 5.3), comments on the impact of swim bench design choices on movement and implications for swim bench application (Section 5.4 & 5.5), and addresses future directions and limitations of this work (Sections 5.6 & 5.7),

5.1 Hypotheses testing

5.1.1 Hypothesis 1: The 3D kinematics of the upper limb and torso during the rotating bench setting trials will differ significantly from the fixed bench setting trials

Hypothesis 1 was rejected. Few of the 3D kinematics of the upper limb and torso during the rotating setting trials differed significantly from the fixed. While the left shoulder elevation angle was greater on the rotating swim bench during the push phase, aligning with the hypothesis, the trunk rotation and remaining shoulder, elbow, and wrist Euler angles did not differ during the pull and push phases. The fixed setting produced greater right wrist ulnar/radial deviation; however, this occurred during the recovery phase, which was not part of the phases of interest explored. Further, in contrast to the hypothesis, none of the stroke characteristics: length, width range, or maximum depth nor the velocity or accelerations of the hand differed between settings.

5.1.2 Hypothesis 2: There will be significant differences in upper limb and torso muscle activation amplitude, timing, and co-activation index between the two settings.

Hypothesis 2 was rejected. Differences existed in the time-series infraspinatus muscle activations; however, the rotating setting did not produce changes in any other muscle activation measures as hypothesized. None of the mean peak muscle activations differed between settings and the supraspinatus, upper and lower trapezius, serratus anterior, pectoralis major (clavicular, sternal, and abdominal regions), anterior, middle, and posterior deltoid, latissimus dorsi, biceps and triceps brachii time-series activations did not differ between settings. The fixed setting produced more infraspinatus activation during the push phase but opposes the hypothesized higher activation during the entry and pull phases on the rotating setting. Finally, no difference existed between settings in the coactivation index for the bicep brachii-triceps brachii muscle pairing.

5.1.3 Hypothesis 3: The 3D kinematics of the upper limb and torso during the swim bench trials will differ from the in-water freestyle pull, regardless of bench setting.

Hypothesis 3 was partially accepted. Differences existed between in-water swimming and the swim bench for all phase durations, stroke length, stroke width measures at the 3rd distal phalanx, wrist, and elbow, 3rd distal phalanx depth range, wrist and elbow depth measures, 3rd distal phalanx peak velocity and accelerations, and total shoulder roll. However, the maximum 3rd distal phalanx depth and elbow flexion angles did not differ between the swim bench and in-water freestyle swimming. Additionally, neither setting replicated the in-water swimming movement more closely than the other.

5.2 Influence of Swim Bench Setting

The rotating setting produced few kinematic and electromyographic changes compared to the conventional fixed bench setting, indicating the rotating setting does not substantially augment the realism of simulated swimming.

5.2.1 Kinematics

The additional roll on the rotating setting did not produce a considerable change in shoulder or hip roll angles on the swim bench. Regardless of setting, participants produced an oscillating roll pattern with similar peak shoulder roll (rotating: $22 \pm 14.7^\circ$, fixed: $19.6 \pm 12.8^\circ$) and total shoulder roll angles (rotating: $36.6 \pm 28.5^\circ$, fixed: $33 \pm 26.3^\circ$). These results correspond with the maximum torso rotation angle of $19.7 \pm 13.2^\circ$ on a Weba swimming ergometer found by Lee et al. (2008), and thus may not be exclusive only to the KayakPro SwimFast. The similarity in peak, total, and time-series roll angles between the settings may be a result of the rotating setting roll allowance not being enough to produce a difference, participants fighting the rotation to stabilize against gravity, as mentioned in the user experience surveys, or from un-explored variables associated with changes at the trunk. The similarity between the 2 settings may also have produced a trickle-down effect into the other measures and help to explain the lack of significant differences found.

The phase durations, and hand trajectories, velocity, and accelerations were similar between settings and likely a result of the similar roll magnitudes. Body roll contributes to the mediolateral hand path during the pull phase, allowing for a wider pulling motion to occur with body roll (Liu et al., 1993; Payton et al., 1997). With only a slight difference in shoulder roll on the rotating setting, it follows that the stroke width would likely be unaffected. Without the shoulder roll participants did not have the added shoulder elevation and glide during the entry

phase or depth during the pull, thus maintaining a similar stroke length and depth, and phase duration between settings (Yanai & Hay, 2000). Additionally, the pulley rope may have guided the motion and reduced mediolateral or vertical trajectory deviations between settings. The greater and delayed anteroposterior deceleration of the left 3rd distal phalanx on the rotating setting just before end-back is notable. The shoulder roll on the rotating setting may still have been enough to contribute to the hand velocity during the sweep-back motion, resulting in a less controlled and delayed hand deceleration closer to the end-back instance compared to the fixed (Kudo et al., 2021).

The laterality differences observed in the entry and pull phase, and the mean stroke width maximum and entry ranges may be a result of the handedness of the participants and the breathing side dominance. An asymmetric, or catch-up, stroke pattern on the dominant side is not uncommon in freestyle stroke mechanics and may reflect observations during the phase durations (Seifert et al., 2005, 2007). During the catch-up stroke, swimmers often spend more time on one arm during the entry and less during the pull phases as the other arm recovers, similar to the longer entry and shorter pull phase durations seen in the swim bench participants (Seifert et al., 2005). The dominant side could have a different pulling pattern with a wider stroke to produce propulsion, explaining the difference in stroke width maximum.

The lack of differences in the shoulder roll and hand path during the propulsive phases are also reflected in the similar joint angles between the settings. The participants did not differ in wrist and elbow rotation or deviation angles because the hand followed the same trajectory and did not require supination for a sculling movement. The hand maintained the same width and depth could contribute to the consistent elbow flexion angle and shoulder horizontal flexion. However, participants produced less shoulder extension on the rotating setting at 56.6 to 62.2

%SC, during the end-back instance into recovery. This may have been a result of the additional 10 degrees of roll on the rotating setting still contributing to the sweep-back movement during shoulder extension (Kudo et al., 2019). The rotation may also have contributed to the slightly greater internal rotation during the push phase on the rotating setting as the participant reached contralateral maximum shoulder roll magnitude.

5.2.2 Muscle Activation Patterns

The majority of the co-activation indices, time-series and peak muscle activations were similar between the settings, reflecting the lack of differences in movement patterns observed. For example, the similarities in biceps brachii and triceps brachii co-activation index, time-series and peak activations between settings is also seen in the similar elbow angle patterns and stroke width path throughout the stroke cycle. In contrast, the infraspinatus time series activation was greater on the fixed setting while the right shoulder axial rotations between 33.4 to 37.7 %SC were not different. Possibly, the increased infraspinatus activation off-sets the greater, but not significant, pectoralis major activation and internal rotation movement during this time period and stabilize the shoulder (Pink et al., 1991). While not significant, the rotating setting consistently had a lower activation profile with more gradual ramping to peak throughout the stroke cycle. Because the stroke frequency and resistance setting were consistent across all trials, it is possible that the rotating setting produced a more economic muscle activation pattern with lower activations to produce the same movement as the fixed setting.

5.3 Freestyle Stroke Simulation on the Swim Bench

The swim bench partially simulated several, but not all, aspects of in-water freestyle swimming. While the hand path, phase durations, and magnitude of shoulder roll on the swim

bench were diminished compared to in-water swimming, the shoulder roll movement pattern and the elbow angles per instance and ranges during the propulsive phases were similar.

5.3.1 Kinematics

The swim bench did not replicate the hand trajectories observed during in-water swimming. Similar to the findings of Piovezan et al. (2019), the resulting stroke length on the swim bench was lower than that of the in-water data and past literature for participants of a similar height (Gonjo et al., 2020; Payton et al., 1999). The difference in stroke length could be a result of the documented limited entry phase duration on the swim bench, where in-water swimmers commonly glide and elongate the stroke (Samson et al., 2015b). In contrast, the stroke depth maximum was similar between the swim bench, McCabe (2008) data, and past literature with similar participant heights (Figueiredo et al., 2013; Payton et al., 1999; Santos et al., 2020). However, the stroke depth range was smaller on the swim bench, which may be from a discrepancy in 3rd distal phalanx depth at the calculated entry instances between the swim bench and in-water data. Finally, the in-water swimming stroke width maximums and range were 10 cm wider compared to the swim bench. The difference in width range and peak may be because swim bench participants produce a straight backwards, I-shaped, pulling path, following the line of resistance along the swim bench pulley, compared to curvilinear changes to the lateral pull direction in-water to generate propulsion and interact with the water (Soh & Sanders, 2021; Takagi et al., 2016).

The anteroposterior velocities and accelerations patterns on the swim bench differ to in-water swimming and appear to diverge from past in-water swimming literature. Unlike in-water swimming, the swim bench produced a peak velocity at the shoulder-x instance, whereas in-water there is a steady increase in velocity with peaks at end-back and entry instances (Figure 5,

Figure 20) (Samson et al., 2015a, 2019). Further, the anteroposterior hand accelerations on the swim bench are in opposition with in-water swimming. The hand accelerates during the entry and plateaus during the pull and push phases in-water, reflected in the marginal mean peak absolute acceleration during each phase (Figure 6) (Samson et al., 2019). Yet, the hand acceleration is stable during the entry and pull on the swim bench and decelerates during the push phase (Figure 21). The difference may be a result of the pendulum movement pattern on the swim bench, where the swimmer slows the hand before the end-back instance to change direction, and the lack of changing resistance between the water and air at hand entry and exit to influence the velocity.

When comparing the phase durations, the swim bench diverged from in-water swimming for every phase. On the swim bench, the 3.8 and 4.8 % SC entry is marginal compared to the 35 % SC in-water. This could be from the lack of glide and stretch during the entry phase that is commonly seen in-water to maintain balance during the transition between push and recovery phases and not necessary on the swim bench (Samson et al., 2015b; Yanai & Hay, 2000). The reduced entry on the swim bench may also bleed into the pull phase, where the hand begins the backwards movement earlier compared to the in-water swimming, elongating the pull phase. Finally, the increased length of the push phase on the swim bench may be from the decreased hand velocity and deceleration to actively slow the hand before end-back and recovery that is absent in-water (Samson et al., 2019).

While the magnitude of roll is not replicated on the swim bench, the movement pattern of the shoulder roll aligns with the McCabe (2008) time-series shoulder roll. The reduction in shoulder roll on the swim bench may be explained by the limited roll allowance on the swim bench to prevent the swimmer from falling, the lack of hip roll and kick involvement to drive the

shoulder roll (Andersen et al., 2020; Sanders & Psycharakis, 2009). The oscillatory rolling movement observed on the swim bench also matches that of the in-water kinematic data and past swimming literature, and the rolling action identified in Lee et al. (2008) on the Weba swim bench (Andersen et al., 2020; Psycharakis & Sanders, 2008, 2010). The earlier timing of the swim bench shoulder roll peaks may also be explained by the shorter entry phase and the participant initiating the pull phase and coincident shoulder roll earlier. Yet, only adjusting the roll at the shoulders on the swim bench may not be enough to fully simulate the freestyle stroke and account for the importance of the hip drive in the rolling action.

Despite the similar rolling action, a lateral torso flexion pattern that opposed the shoulder roll timing occurred on the swim bench. The lateral bending and fish tailing motion may have resulted from the lack of roll allowance at both the shoulders and hips. As compensation, the lateral torso flexion may have allowed participants to achieve the shoulder adduction and elevation needed to begin the propulsion during the pull phase and produce greater anteroposterior hand velocity as the participants approached the end back instance during the push phases (Riewald & Rodeo, 2020, pp. 26-27; Yanai & Hay, 2000).

In contrast to the other measures, the elbow flexion angles on the swim bench replicated those observed during in-water swimming. While the hand path on the swim bench deviated from in-water swimming, the width and depth positioning of the elbow relative to the wrist and shoulder may have been similar enough to generate similar elbow flexion angles between conditions.

5.3.2 Muscle Activation Patterns

Compared to the electromyography in swimming literature, the time-series muscle activation patterns on the swim bench approximated; however, the timing of the peaks were

shifted earlier in the stroke cycle, the mean peak activations were lower, and the biceps brachii-triceps brachii co-activation index differed during the propulsive phases. The shift in activation timing of the pectoralis major, biceps brachii, upper trapezius, supraspinatus, serratus anterior, posterior deltoids, latissimus dorsi, and triceps brachii, on the swim bench may have been influenced by the lack of entry phase, earlier initiation of the backward hand movement, and different timing of the stroke instances (Clarys, 1988; Martens et al., 2015; Pink et al., 1991). Due to the nature of the swim bench recovery movement, the activation peaks during the overhand recovery were missing for the middle deltoid, anterior deltoid, and infraspinatus (Martens et al., 2015; Pink et al., 1991). Of the musculature evaluated on the swim bench, only the posterior deltoid generated a peak activation close to past literature (Fixed: 30 % MVIC, rotating: 29 % MVIC, versus Clarys (1988) in-water: 27 % MVIC) (Clarys, 1988). The lower mean peak muscle activations on the swim bench may have been from a difference in resistance and force requirements. On the swim bench, the participants were supported by the bench, the fly wheel provided anteroposterior resistance, and participants moved through air as opposed to the in-water conditions that require swimmers to maintain body position in water and pull against a denser, multi-directional, water resistance (Schleihauf, 1983). The disparity in force generation demand on the swim bench compared to in-water swimming may contribute to the lower mean peak muscle activations observed. Finally, the co-activation index of the bicep brachii-triceps brachii pairing was higher during the pull phase on the swim bench compared to Lauer et al. (2013), yet lower during the push phase. However, the pattern of a higher co-activation index during the pull phase and elbow flexion compared to the push phase coincides with Lauer et al. (2013), and reflects the elbow loading and flexion angle similarities between the swim bench and in-water swimming (Lauer et al., 2013; McCabe, 2008).

5.4 Impact of swim bench design

The swim bench design choices likely effect the movement patterns observed on both settings and the differences to in-water swimming. While the swim bench must trade off between body roll realism versus stability, the rotating setting allowance is still not enough to produce notable differences in movements and muscle activation between settings. The length of the rotating section may contribute to the lack of roll allowance and potentially was not long enough to produce full shoulder roll. In taller athletes especially the division between the rotating and fixed sections may sit higher on the torso limiting the roll ability. Further, the division between the rotating and fixed sections is above the hips, most likely to provide the athletes stability while using the rotating setting. Yet, the body roll in freestyle swimming is a combination of separately rolling shoulders and hips and the design choice to keep the hips fixed neglects the contribution of hip roll to overall body roll and the hand acceleration during the push phase (Psycharakis & Sanders, 2008, 2010). Similar to the hips, the legs are fixed with the feet anchored for stability on the swim bench. This set up represents swimming with a pull buoy rather than the full freestyle stroke. The anchored feet also limit the athlete's ability to incorporate the kicking motion involved in the body roll and the cross-body connection during entry to pull phases (Sanders & Psycharakis, 2009). Additionally, the bench is on an upward incline toward the head compared to a level body position at the water surface during the freestyle stroke. This incline may have added to the participant's apprehension on the rotating setting and fear of falling off . Separately, the configuration of the pulley, hand paddle size, and centered rope attachment location may influence the wrist flexion and extension observed during the push phase and the lack of mediolateral hand path deviations. The path of the pulley and the centered attachment point to the paddle may guide the hand along a straight back motion and

limit mediolateral pressing against the paddle, which does not reflect the mediolateral movements and changing hand direction during the pull phase in water (Kudo et al., 2023; Soh & Sanders, 2021). During the push phase and sweep-back movement, swimmers may have flexed and extended their wrist to maintain the pressure along the palm and accommodate the centered rope attachment point to the standard handle with contact points only at the mid palm instead of the whole hand.

5.5 Implications for swim bench application

This thesis provides novel data and adds to the sparse literature evaluating the efficacy of the swim bench to simulate swimming. Building on past evaluations by Olbrecht & Clarys (1983) and Piovezan et al. (2019) this thesis provides additional findings regarding elbow flexion angles, stroke cycle phase durations, and total shoulder roll compared to in-water swimming and introduces muscle activations of the rotator cuff, scapular stabilizers, clavicular and abdominal pectoralis major regions, and middle deltoid. Additionally, the potential influence of shoulder roll on a swim bench is quantified, which to our knowledge had not been evaluated yet. The results can further guide the use of the swim bench in training and research.

The rotating setting may not substantially augment freestyle stroke simulation; thus, athletes can choose the more comfortable setting. Although the rotating setting allowed for greater left shoulder elevation during the push to recovery phase transition and left shoulder internal rotation during the push phase, the fixed setting produced greater infraspinatus activation during the pull to push phase transition and no other significant differences between settings existed. Additionally, neither setting aligned more closely with the in-water kinematics. Athletes also had no distinct preference for either setting, despite the rotating setting feeling the closest to their in-water technique for the majority of the users. Further, the swim bench did not cater to

one freestyle swimming distance specialty. While the limited shoulder and hip roll allowance and straight hand path with little mediolateral deviation observed on the swim bench aligned with the lower shoulder and hip roll and straight back, I shaped, pull pattern often adopted by sprint freestyle specialists, the swim bench lacked contribution of the lower limb, kick, and hip roll that drives the freestyle stroke (Castro et al., 2006; Psycharakis & Sanders, 2010; Sanders & Psycharakis, 2009; Takagi et al., 2016). Without the kick and lower limb contribution, a swimmer cannot directly transfer the swim bench movement to in-water swimming for sprint and middle-distance. Contrastingly, the lack of kick on the swim bench may make it more suitable for a distance freestyle specialist, however the lack of roll allowance didn't align with reported shoulder roll characteristics in distance swimming paces (Andersen et al., 2020; Castro et al., 2003). Thus, swimmers can choose the setting that is the most comfortable and aligns with their individual style of swimming, regardless of distance specialty.

Despite potential benefits, long term swim bench use in training may develop swimmer habits that reduce swimming economy, increase drag, and worsen shoulder pain when translated into the water. A narrower stroke width on the swim bench could affect propulsion during the propulsive phases, since a wider mediolateral hand displacement is associated with higher propelling efficiency in-water (Soh & Sanders, 2021; Takagi et al., 2016). Without an entry phase on the swim bench, swimmers also do not train the hand propulsion associated with the entry and downsweep (Kudo et al., 2023; Psycharakis & Coleman, 2024). Changes to shoulder elevation and wrist flexion and radial deviation on the swim bench may reinforce stroke mechanics that affect force production. Less shoulder extension during the push phase and end-back instance may result in lower hand velocity and force generation, while the lack of a stable, neutral wrist posture, as observed on the swim bench, can reduce the force transfer along arm

during the pull and push phases (Caty et al., 2007). Further, the reduced shoulder and hip roll may lower force generation because the hand acceleration associated with the rolling action is diminished on the swim bench (Kudo et al., 2019). Training a freestyle stroke with no hip drive can also result in reduced propulsion since the hips and kick drive the stroke and act as a cross-body connection between the legs and arms (Sanders & Psycharakis, 2009). The addition of the lateral torso flexion on the swim bench, if translated to in-water swimming, may create additional drag, thus slowing the swimmer. Finally, swimmers with shoulder injuries should approach swim bench use with caution. By design, the swim bench forgoes the use of the legs and emphasizes the shoulders and arms, which may further aggravate shoulder injuries. Additionally, if similar to in-water swimming, the reduced hip roll on the swim bench may contribute to unilateral shoulder pain with use (Vila Dieguez & Barden, 2022). When put into practice, habits of a narrow stroke width, increased wrist flexion and radial deviation, reduced shoulder extension and torso roll, and added lateral torso flexion from swim bench training could negatively affect a swimmer's freestyle swimming mechanics and enhance shoulder complications.

Within research, studies that use the swim bench may not accurately reflect the realities of in-water swimming and the movement pattern on the swim bench may not be task-specific for results to extrapolate to the pool. The swim bench introduced movements not seen during in-water freestyle swimming and the propulsive phase movements deviated in muscle activity, co-activation, wrist flexion, phase duration, shoulder roll magnitude, and stroke width. Participants actively slowed their hands at the entry and end-back instances, adding muscular effort not seen during the cyclic movement of in-water swimming. Further, the recovery on the swim bench is underhand and passive, changing the muscle activity at the upper trapezius, lower trapezius,

middle deltoid, and anterior deltoid; thus, reducing muscular effort and providing an extra resting time period with every stroke. The elongated recovery period on the swim bench also adds to the rest period, further reducing exertion. Although, the swim bench activation patterns during the propulsive phases and the peak posterior deltoid activation were close to in-water, prime movers such as the biceps brachii, pectoralis major, triceps brachii, and latissimus dorsi were under activated in comparison (Clarys, 1988; Martens et al., 2015; Pink et al., 1991). Additionally, the higher biceps brachii-triceps brachii co-activation index during the pull and lower co-activation index during the push on the swim bench suggest that, while the elbow angle was consistent between in-water freestyle swimming and the swim bench, the muscle firing necessary to produce it is different (Lauer et al., 2013). As mentioned, the reduced shoulder roll magnitude, narrower stroke width, and lack of shoulder extension at end-back may reduce the possible propulsion and force generation on the swim bench during the push and pull phases, respectively (Falk Giuliano et al., 2022; Kudo et al., 2019; Payton et al., 2002). If the movement is not the same on the swim bench and cannot produce similar demands, energetics and fatigue study results from the swim bench may underestimate the realities of swimming. Additionally, relationships between performance and power on bench may not be accurate because the swim bench mechanics lacks key force generation movements and are not sport specific enough to identify an association.

Despite these considerations, the swim bench still has valuable applications. The majority of participants expressed interest in the use of the swim bench for swimming technique correction or circuit training, indicating that athletes see value for the device's use in training. Further, the swim bench could be a useful tool when teaching pre-competitive or beginner level competitive swimmers and providing directed feedback with movement manipulation on land.

The maximum resistance setting, and stroke frequency used in this thesis may have been too low to produce physiological changes during use; therefore, when used in circuit training or energetics research, a greater stroke frequency and effort level may be required to induce sport specific changes in maximal oxygen consumption and mechanical power output. While both settings demonstrated lower muscle activation patterns compared to in-water swimming literature, the swim bench could be useful for priming the muscular system during warm-ups before training or as a return to sport protocol alternative. Swimmers with lower limb injuries or concussions could also use the swim bench to supplement return to sport training. Further, upper limb and elbow flexion technique manipulation and correction that cannot be done from the side of the pool is possible on the swim bench, especially because the elbow flexion angles are similar between in-water swimming and the swim bench (Stott, 2018). The swim bench cannot replace in-water swimming, but it could positively supplement training when its limitations are understood.

5.6 Future Directions

Although this thesis builds another knowledge layer concerning swim bench biomechanics during simulated swimming, there are many next steps that could expand understanding of the swim bench compared to in-water swimming. In continued collaboration with Dr. McCabe, additional analyses of the time-series kinematic data and a comparison between swimming distance specialty groups can be explored. Beyond this work, repeated measures studies directly comparing the upper limb and torso joint angles and electromyography between in-water swimming and the swim bench are necessary to further appraise the accuracy of the in-water swimming replication on the swim bench. To approach the torso compensations and lateral flexion on the swim bench, the torso musculature and kinematics on land and in-water

can be studied. For training implementation, long-term translations of the swim bench mechanics to in-water swimming should be explored to identify training effects and inform coaches.

5.7 Limitations

5.7.1 Sample Size

Fifteen participants for paired and independent samples t-tests are likely under powered. Some of the measures, such as the left third distal phalanx anteroposterior acceleration and shoulder axial rotation, bordered on demonstrating significant differences. While not statistically significant, the left third distal phalanx anteroposterior acceleration and shoulder axial rotation differences were meaningful, and, potentially, with a greater sample size these differences may have reached significance.

5.7.2 Participant Variance

There is potential for differences between the swim bench and in-water swimming kinematics to have arisen from variance between participant anthropometrics, freestyle stroke mechanics, and level of competition; therefore, population-level trends may be the extent of plausible comparisons. This was partially mitigated by matching the swim bench participants' competition level and personal best times within the ranges of the McCabe (2008) inclusion criteria. Independent samples t-test were performed between groups, and no differences existed between group height, weight, and 50 and 400 m freestyle SCM times. However, any differences in anthropometrics and differing segment lengths have the potential to influence the differences in the mean maximum stroke length and depth. Further, while swim bench participants were screened for hand dominance, breathing side dominance was not recorded in either group, which may have influenced the freestyle stroke mechanics and influences of laterality.

5.7.3 Swim Bench Resistance Setting and Stroke Frequency

The chosen resistance setting on swim bench was based on past literature, which included subjective appraisal by swimmers between their feel for the water and the resistance provided by the bench (Edelmann-Nusser et al., 2004). However, the majority of participants indicated that the resistance provided on the swim bench did not feel similar to the water, more specifically the bench-provided resistance was perceived as easier and was only applied at the hand instead of the entire arm. The difference in resistance combined with a lower stroke frequency may have influenced the magnitude of muscle activations captured on the swim bench and participants may have found the task easier than what is commonly encountered during practices and races.

6.0 Conclusion

This thesis demonstrated key differences between swim bench and in-water swimming kinematics and further developed knowledge of swim bench use as a surrogate for freestyle swimming. Additionally, this thesis considered the contribution of body roll during freestyle swimming and evaluated the influence of a rotating setting on swim bench kinematics and muscle activations. The addition of a rotating swim bench setting did not augment the fidelity of simulation of swimming on land, and the swim bench marginally replicated the movement patterns. The novel findings of this thesis can inform coaches and researchers on the considerations and limitations of the swim bench and help guide its application in competitive swimming.

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Appendix A: User Perception Survey

1. Demographic/Background information

a. What is your age? _____

b. What is your sex assigned at birth

Male

Female

2. Which setting did you most prefer?

1
(Rotating)

2
(Fixed)

3
(Neither)

Comments: _____

3. Which setting felt closest to your in-water technique?

1
(Rotating)

2
(Fixed)

3
(Neither)

Comments: _____

4. The swim bench resistance felt similar to in-water swimming resistance

5
(Strongly Disagree)

4
(Disagree)

3
(Neutral)

2
(Agree)

1
(Strongly Agree)

Comments: _____

5. The swim bench was intuitive to use

5
(Strongly Disagree)

4
(Disagree)

3
(Neutral)

2
(Agree)

1
(Strongly Agree)

Comments: _____

6. What is your perspective of the swim bench movement (e.g., general similarities vs differences to in-water, likes vs dislikes)?

7. You would use the swim bench in your training if provided

5	4	3	2	1
(Strongly Disagree)	(Disagree)	(Neutral)	(Agree)	(Strongly Agree)

Comments: _____

8. Have you used a swim bench before

1	2
(yes)	(no)

If yes, please answer the following -

a. How long ago did you use the swim bench?

5	4	3	2	1
(< 1 year)	(1 year ago)	(2 years ago)	(3 years ago)	(> 4 years ago)

b. What was the swim bench used for?

c. Did you feel the swim bench accomplished it's intended use?

1	2
(yes)	(no)

Comments: _____

9. Additional comments: _____

THANK YOU!

Table 17. *User Experience Survey Comments*

	<i>Perspectives</i>	<i>Preferred Setting</i>	<i>Similarity to in-water technique</i>	<i>Resistance compared to water</i>	<i>Would they use the swim bench if provided?</i>	<i>What was the swim bench used for (past use section)?</i>
S01M	Able to catch air just like in water. Less core engagement since no kick.	Static felt easier	Rotating engaged lats more	Water resistance feels stronger	Good application for stroke correction and potentially injury prevention.	
S02M	Not having to recover is awkward. Don't have to twist head to breath. Handles weird to hold on to so hand position feels compromised.	Static requires more core engagement and harder on the shoulders		Lighter than water.		
S03M	Pulling similar. Swim bench couldn't rotate enough to mimic swimming, may have impacted stroke.	Rotating felt unstable. Not sure if enough rotation to mimic swimming	Other than pull, swim bench can't accurately replicate swimming (hand recovery, breathing, etc.)		Could work on technique with.	Technique correction
S05M	Very helpful fitness wise. Does not provide an aid for technique.	Rotating felt like falling off	Rotating was jerky	Resistance at arm/shoulder felt similar, at hand/wrist not	Circuits on swim bench could improve fitness.	
S06M	Rotating feels better but still not exactly like in-water. During active rest, felt harder to go slow than would be in water.	Rotating more natural and able to get efficient pull	Rotating makes a difference	First pull always harder than the rest, otherwise felt similar	Would only use if pools were closed.	Station in circuit training.

S07M	Rotation felt unnatural and made pull awkward. Swim bench doesn't rotate enough. Pressure only at the hands instead of the whole arm.		Neither (straight arm swimmer)"	Pulling weight similar, but all resistance at hands whereas in water would be at forearms and elbow too		
S08M	Natural twist response to pull not quite there on bench. Level and consistency of force is different to water.		Rotating feels needed on bench, but slightly different and not as natural	Technique similar but level of force applied different	Great way to train on land and easier to correct mistakes in technique.	
S09M	Harder to mimic body roll because of gravity. Different muscles used because arm heavier on land than in water (specifically stabilizers?). Adjustable head position would be nice, head felt too high vs. body.	Head rotating with the body is weird/hard to get used to		Pressure along pull path is different. Increase hand speed = increase pressure in water, but here it get's easier	Mimics stroke well, if could increase resistance more, might be beneficial.	
S10M			Near impossible to actually replicate (in-water = straight arm swimmer)	More slip at top of stroke (catch) and not even resistance through pull	Not a bad tool to add along side in-water to work on pull but would not do bulk of training on it.	Training during COVID-19 pool closures
S12M	Prefer in-water but good substitute.			Slightly more difficult starting up	Once in a while for circuits.	
S13M	Felt like forearm and lat workout, doesn't hit triceps as much because of changing angle of cable as hand moves vertically. Don't like the frame since it inhibits the power triangle (hand closer to center line at bottom of stroke).	Static felt like pulling with a pull buoy	Rotating more driven by kick and not shifting upper body	Can produce more power in water during catch since start with hand parallel to surface. Can't do with swim bench/would let go of paddles.		For fun

S14M	First few strokes more difficult than the rest. No overhead recovery removes the water entry aspect of the catch.					
S17M	Harder to keep high catch due to lack of water resistance. Prefers proper/overhead recovery.			High start up resistance		Strength training
S18M	Might be better for butterfly. Rotate more in-water than on the bench, does simulate though.	Static felt easier to pull	Felt easier to rotate on one side than other	Small pull at beginning but not much resistance after. Easier than in water.	Didn't feel benefit at slower speed, maybe if pulling faster	Measuring pull power
S19M	Degrees of movement not similar (e.g. no hip rolling and head moved).		Little relationship to swimming	Head rolled with shoulders and caused resistance to apply at an odd head position		

Appendix B: McCabe (2008) In-Water Data

Participants

15 male participants, with Scottish national and international time standards in freestyle swimming distance and sprint races, were recruited for the McCabe (2008) study. Participants varied between distance and sprint freestyle stroke specializations (sprint = 7, distance = 8) (McCabe, 2008). The mixture of sprint and distance freestyle stroke specialists will also allow for easier swim bench recruitment, since one specialization will not have to be focused on.

Experimental Set Up

For underwater collections, the anatomical markers were marked, using black waterproof oil and wax-based cream, on vertex of head and bilaterally on the 3rd distal phalanx of the finger, wrist axis, elbow axis, shoulder axis, hip axis, knee axis, ankle axis, fifth metatarsophalangeal joint, tip of first phalanx of the toe (McCabe, 2008).

The capture volume in the pool was calibrated using a rectangular prism frame (McCabe, 2008). 6 Gen-locked JVC KY32 CCD cameras were used, 2 above water level and 4 underwater (McCabe, 2008). All cameras recorded at a sampling rate of 50 Hz with a shutter speed of 1/120 seconds (McCabe, 2008).

Experimental Protocol

Participants performed 4, 25-meter sprints from a push start (McCabe, 2008). After every sprint, participants actively recovered with a 25-meter swim back to the starting position and rested for 2 minutes (McCabe, 2008).

Processing

Above and below water views were digitized separately with direct linear transformation algorithms (McCabe, 2008). The 3D coordinates of the anatomical landmarks from the 2 views were combined for continuous coordinates through the freestyle stroke cycle (McCabe, 2008).

Analyses to calculate all variables were performed in MATLAB (Mathworks, Inc) (McCabe, 2008). To smooth the raw data of the stroke cycle, a Fourier transform retaining 6 harmonics was used (McCabe, 2008). Body segment parameters were calculated using the elliptical zone method in the “eZone” program and inputted into the MATLAB program for whole body center of mass positioning and velocity (McCabe, 2008).

Analysis

The 4 phases of the stroke cycle were defined as the entry, pull, push, and recovery, and determined from the horizontal and vertical displacement of the finger (McCabe, 2008). Vertical motion was defined in the z axis, backwards or horizontal motion in the x axis, and lateral motion in the y axis (McCabe, 2008).

One stroke cycle per 25-meter sprint was analyzed and all kinematic measures were averaged across the 4 trials (McCabe, 2008). Computed measures and results can be found in figure 10 and 11. Phase duration was represented as percent stroke cycle (Figure 11) (McCabe, 2008). Participant stroke length was calculated as the center of mass horizontal displacement through one stroke cycle while the average horizontal velocity was calculated as the participant's mean center of mass horizontal displacement divided by the time to complete one stroke cycle (McCabe, 2008). Stroke frequency was defined as the time (seconds) to complete one stroke cycle over 1, and was then multiplied by 60 to provide the measure in strokes per minute c.

Stroke depth was calculated as the z displacement (m) for the 3rd distal phalanx of the finger, wrist axis, and elbow axis (McCabe, 2008). Stroke width was calculated as the absolute y displacement (m) of the 3rd distal phalanx of the finger, wrist axis, and elbow axis (McCabe, 2008). The elbow angle ($^{\circ}$) was calculated as the arccosine of the dot product between the humerus and forearm unit vectors at four instants during the underwater phases and through the range of the pull and push phases (McCabe, 2008). The shoulder and hip roll angles ($^{\circ}$) were calculated as the angles between the unit vector joint the shoulder and hip joints, projected onto the y-z plane and the horizontal, or as the arc-tangent of each z and y components of the shoulder and hip respectively (McCabe, 2008).