



## BODY STABILITY AND SUPPORT SCULL KINEMATIC IN SYNCHRONIZED SWIMMING

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### ABSTRACT

**Purpose.** The aim of this study was to examine the dependencies between support scull kinematics and body stability in the vertical position. **Methods.** The study involved 16 synchronized swimmers. Twelve markers were placed on the pubic symphysis, head, middle fingers, and transverse axes of upper limb joints. Support scull trials were recorded at 50 fps by cameras placed in watertight housings. Calculated measures included: excursion of the sculling movement; flexion and extension angle of the elbow and wrist joints; adduction and abduction angle of the shoulder joint; adduction and abduction angle of the forearm to/from the trunk; range of movement of the wrist, elbow, and shoulder joints; range of movement of forearm adduction towards the trunk; and the range of movement of shoulder adduction towards the trunk. **Results.** The length of the trajectory taken by the marker on the pubic symphysis was longer if the range of movement of the wrist joint was larger. The movement of the body in the right-left and upwards-downwards direction increased together with a greater range of movement of the wrist joint. It was also found that a greater sculling angle produced greater body displacement in the forwards-backwards direction. The head marker was characterized by a significantly larger range of displacement in the forwards-backwards and right-left directions than the pubic symphysis. **Conclusions.** The findings indicate that the ability to maintain body stability in the vertical position is associated with the range of movement of the radial wrist joint, angle of forearm adduction, and a newly-introduced measure – sculling angle.

**Key words:** sculling, vertical position, swimmer

### Introduction

The relatively small (compared with other sports) number of scientific publications on synchronized swimming can be explained by the fact that it is still a new, albeit rapidly growing, discipline. A review of the available literature finds reports that have attempted to: determine the total duration and number of times swimmers spend underwater during a solo routine [1], measure the effects of propulsive sculling action in horizontal body displacement [2], compare the efficiency of repetitive arm movements by synchronized swimmers and artistic gymnasts [3], measure the force produced in standard and contra-standard sculling [4], search for a relationship between eggbeater kicking skills with leg and trunk muscle strength and the technical skills needed to maintain the vertical position [5], determine unhealthy behaviors in swimmers and examine the relationships between perfectionism, body esteem dimensions, and restrained eating [6], assess the effects of vibration and stretching on passive and active forward split ranges of motion [7], and evaluate the dynamic asymmetry of support sculling [8]. However, few studies have dealt exclusively with analyzing the synchronized swimming technique. One reason may stem from the necessary albeit complex demands of recording synchronized swimming movements underwater.

Synchronized swimming is a branch of swimming in which swimmers compete by executing a specific movement routine composed of numerous technical elements. This discipline is dominated primarily by movement sequences performed in an upright (vertical) position, with the head above or under water. A more comprehensive literature review found a limited number of studies analyzing lower limb movements such as the eggbeater and boost kicks, techniques which allow swimmers to move or rise out of the water or maintain the body in the vertical position [9–11]. Some congruency between these swimming techniques and those used in water polo was found [12]. However, few have examined the employment of the upper limbs in synchronized swimming. Although the use of the upper limbs when underwater (termed as sculling) is not subject to scoring during competition, the upper limbs are essential in synchronized swimming performance as they allow a swimmer to execute various movement routines and figures in both static and dynamic conditions. Two commonly executed sculls are the standard scull and support scull. The standard scull (and contra-standard) is used to align the swimmer's body in the layout position whereas the support scull is employed to maintain the vertical position, with the head above or under the water. Support scull has been described as one of the most difficult techniques in synchronized swimming since it involves steadily and smoothly displacing the body while maintaining a part of it above the water [13]. During vertical position maintenance, with head above

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the water, correct sculling technique requires an elbow flexion angle of  $90^\circ$  while maintaining the arm in a relatively stationary position with the forearm performing the sculling motion [14]. Conversely, in order to keep the swimmer's body in the vertical position with head under the water, swimmers hold their elbows and upper arms stationary whereas the forearms are kept horizontally at  $110\text{--}145^\circ$  of elbow flexion [13]. Analysis of support scull kinematics in the vertical position (head under water) was found to differ depending on the length of the lower limbs [15]. During sculling the hands of swimmers typically execute a "figure 8", egg-shaped oval, or ellipse movement [2, 16]. Another alternative is to use hand dorsiflexion. Some sculls, such as the reverse, dolphin, and alligator sculls use a technique involving palmar flexion. Sculls performed with both palmar and dorsal flexion allow swimmers to rotate and twist when in the vertical position [17]. One study to date has attempted to determine the most efficient hand configuration for generating maximal lift by hydrodynamic analysis [16]. Additional interest in sculling technique stems from the fact that synchronized swimming is a subjectively judged sport, where criteria such as the accuracy in executing various figures as well as the ability to maintain the body in a high and stable position above the water are very important. Furthermore, the difficulty in learning the necessary skills to support the body in the inverted vertical position, which takes up to two years according to coaches, warrants additional research on synchronized swimming technique and the ability of the swimmer to maintain body stability in the water.

A review of the available literature shows no investigation on the correlations between the kinematic variables associated with support scull technique and balance. One available publication has analyzed the kinematic variables of sculling in elite synchronized swimmers able to maintain nearly perfect body balance, leading them to create an elite movement model but this is based on swimmers that demonstrated proficient and balanced support scull [10]. The difficulty in learning the necessary skillset to support the body in the inverted vertical position can take up to 2 years according to coaches and therefore warrants the need for additional research on support scull technique in order to ascertain technique efficacy.

Therefore, the aim of the present study was to search for correlations between support scull kinematics (with the introduction of a new angular variable to quantify the support scull movement cycle) and the ability to maintain balance in the inverted vertical position. Although the biomechanical investigation of synchronized swimming technique – in contrast with competitive swimming [18] – is not directly associated with achieving competitive success, it can aid in the identification of the factors responsible for technique execution and therefore contribute to enhanced performance.

## Material and methods

The sample consisted of 16 female synchronized swimmers with varying levels of performance, from beginners (juniors) to experts (master class). Mean ( $\pm$  SD) age, body mass, and body height was  $15.9 \pm 3.5$  years,  $51.9 \pm 6.2$  kg, and  $160.6 \pm 6.2$  cm, respectively. Written informed consent was obtained from the guardians of the participants as was approval from the local ethics advisory committee.

Optimum conditions were ensured in order to provide high-quality data acquisition [19]. Two digital JVS video cameras recording at 50 fps and 100 Hz, placed in watertight housings, were affixed perpendicularly to the walls of a pool. A frame of reference in the shape of a rigid cube ( $1\text{ m}/1\text{ m}/1\text{ m}$ ) with six selected reference points was used during filming. Both cameras were synchronized with a flash of light. Twelve markers (Figure 1) were drawn on the swimmers' bodies corresponding to the transverse axes of the shoulder, elbow, wrist, and hip joints and on the pubic symphysis, head, and right and left middle fingers. The markers were 1 cm in diameter and drawn with a waterproof pen directly on the body. Each participant was then filmed performing

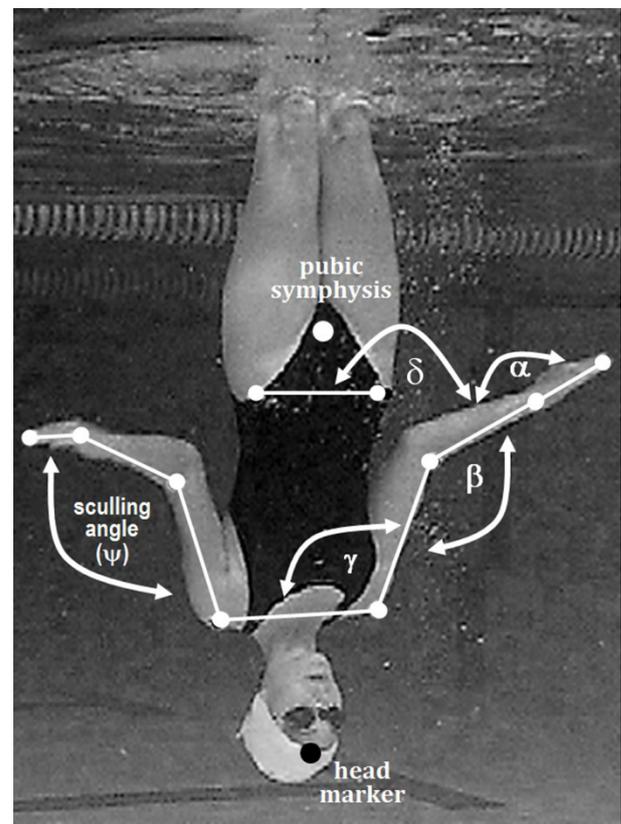


Figure 1. Location of body markers to define flexion and extension angle of the wrist joint ( $\alpha$ ), flexion and extension angle of the elbow joint ( $\beta$ ), adduction and abduction angle of the shoulder joint ( $\gamma$ ), adduction and abduction angle of the forearm to/from the trunk ( $\delta$ ), sculling angle ( $\psi$ )

three trials of eight support scull cycles with both lower limbs extending out of the water. The experiment was preceded by a warm-up and all participants wore swimsuits, caps, swimming goggles, and nose clips.

Support scull kinematics was quantified using SIMI Motion® software by assessing individual movement cycles. Since sculling is performed in all three anatomical planes, the breakdown of this movement based on only the angle created by the elbow joint was considered insufficient. Therefore, we adopted the angular motion made at both the elbow and wrist joints (measured by the shoulder, elbow, and middle finger markers). This angle was defined herein as the sculling angle ( $\psi$ ). The sculling movement cycle was then delineated by the changes in the sculling angle, where the first phase of the sculling movement cycle was treated as the minimum to maximum sculling angle and the second phase of the sculling movement cycle as the maximum to minimum value. Based on these phases, the following temporal and kinematic characteristics of the sculling movement cycle were considered:

- duration of the sculling movement cycle [s]
- duration of the first and second sculling cycle phases [s]
- trajectory length of the sculling movement (based on the displacement of the middle finger marker) [m]
- flexion (palmar flexion) and extension (dorsiflexion) angles of the wrist joint ( $\alpha$ ) [°]
- flexion and extension angles of the elbow joint ( $\beta$ ) [°]
- adduction and abduction angles of the shoulder joint ( $\gamma$ ) [°]
- adduction and abduction angles of the forearm to/from the trunk ( $\delta$ ) [°]
- sculling angle ( $\psi$ ) [°]
- ranges of movement of the radial wrist, elbow, and shoulder joints [°]
- range of movement during forearm adduction towards the trunk [°]
- range of movement during shoulder adduction towards the trunk [°]

The angles defined in the study are shown in Figure 1. Body stability during the support scull was assessed by measuring:

– trajectory created by the head and pubic symphysis markers (over subsequent scull cycles)

– marker displacement in the forward–backward (frontal plane), right–left (sagittal plane), and upward–downward (transverse plane) directions (for each scull cycle) [m].

Statistical analysis was performed using Statistica v 9.1 software. Means and standard deviation were calculated for all variables. The one-sample Kolmogorov–Smirnov test was used to examine the normality of data distribution. Non-parametric measures were then applied (Wilcoxon signed-rank and Spearman's rank correlation tests). Differences were considered significant when the probability was at  $p \leq 0.05$ .

## Results

For this purpose, the mean displacement of the two markers placed on the pubic symphysis and on the head was calculated in three anatomical planes. Additionally, another criterion was the measurement of the length of the trajectory taken by the markers located on the pubic symphysis and head (Table 1).

To research the relationship between the kinematic variables of sculling and body stability the criteria for assessing body stability should be determined. The first criterion was the displacement of the swimmer's body in three directions. Differences in upward–downward displacement and trajectory length of the head and pubic symphysis markers were not statistically significant. However, the head marker was characterized by significantly ( $p \leq 0.05$ ) greater range of displacement in the forward–backward and right–left directions than the pubic symphysis. This finding suggests the important role of head movement in correcting sway when submerged under the water. For the remainder of the present study we assessed body stability with the pubic symphysis marker.

Analysis of the angles as well as ranges of movement found the largest range of movement was exhibited in forearm adduction (Table 2). This movement was also found to feature the smallest variability among the swimmers. The smallest range of movement yet with the

Table 1. Mean displacements and trajectory lengths (per scull cycle) by the pubic symphysis and head markers

Variable	Direction	Mean $\pm$ SD	Coefficient of variation (%)
Displacement (m)	Head marker	Forwards–backwards	0.044 $\pm$ 0.010
		Right–left	0.028 $\pm$ 0.007
	Pubic symphysis marker	Upwards–downwards	0.034 $\pm$ 0.015
		Forwards–backwards	0.028 $\pm$ 0.016
		Right–left	0.023 $\pm$ 0.010
		Upwards–downwards	0.034 $\pm$ 0.010
Trajectory length (m)	Head marker	0.13 $\pm$ 0.06	51.19
	Pubic symphysis marker	0.12 $\pm$ 0.09	65.52

\* statistically significant difference  $p \leq 0.05$

greatest amount of variability was found in the wrist joint angles.

For the sculling angle, the first phase (lateral shoulder movement) was significantly ( $p \leq 0.05$ ) shorter in duration than the second phase (medial shoulder movement) (Table 3).

Correlational analyses were performed between the range of displacement and the trajectory of the pubic symphysis marker (Table 1) and skull kinematics (Table 2). A statistically significant relationship (Spearman's  $r = 0.621$ ,  $p < 0.01$ ) was found between the trajectory of the pubic symphysis marker and radial wrist joint range of movement. The range of displacement of the pubic symphysis marker (and thus the body of the swimmer) in the right-left direction was positively correlated (Spearman's  $r = 0.602$ ,  $p < 0.013$ ) with the range of movement of the wrist joint and negatively correlated (Spearman's  $r = -0.720$ ,  $p < 0.001$ ) with forearm adduction towards the trunk. Movement in the forward-backward direction correlated (Spearman's  $r = 0.547$ ,  $p < 0.028$ ) with sculling angle, whereas upward-downward movement correlated (Spearman's  $r = 0.614$ ,  $p < 0.011$ ) with the range of movement of the radial wrist joint.

Comparisons were made between the angular kinematics of those who presented the least (A) and most (B) sway (best and worst stability, respectively) in order to determine a frame of reference for support scull technique. The trajectory length of the pubic symphysis marker in one support scull cycle in the least stable swimmer (B) was 0.10 m, whereas the swimmer with

the greatest stability (A) showed only 0.05 m sway. The displacement of the pubic symphysis marker in swimmer B in all three anatomical planes was twice as large as that in swimmer A. The differences in sculling technique by swimmers A and B are illustrated in Figure 2, which presents the trajectories of the right and left middle fingers in all three anatomical planes. Differences between both swimmers were also found in the shape of the trajectories as well as in the amount of upper limb asymmetry.

### Discussion

The purpose of this study was to describe the movement technique used in sculling and determine the kinematic variables associated with maintaining stability in the inverted vertical position. For this purpose, we proposed the division of the sculling movement into cycles and phases by the use of a newly introduced measure, the sculling angle, calculated by the movement of the elbow and wrist joints. The minimum and maximum angular values were used to quantify the entire sculling movement into an initial phase (abduction and second phase (adduction). However, the linear and angular values we obtained are difficult to compare with the results of other authors as different criteria were used to quantify the sculling movement. Nonetheless, a comparison of the duration of the sculling movements found that the present support scull cycle times were similar to the ones reported in other papers [20, 21, 15]. The

Table 2. Range of movement (°) for the right and left limb during a sculling movement

Range of movement	Right upper limb		Left upper limb	
	Mean ± SD (°)	Coefficient of variation (%)	Mean ± SD (°)	Coefficient of variation (%)
Sculling ( $\psi$ )	57.05 ± 10.96	19.20	56.38 ± 13.30	23.6
Elbow joint ( $\beta$ )	50.61 ± 10.77	21.27	49.99 ± 19.15	38.3
Wrist joint ( $\alpha$ )	26.80 ± 5.65	21.07	31.15 ± 9.6	30.72
Forearm abduction/adduction ( $\delta$ )	91.67 ± 7.65	7.66	91.77 ± 7.8	8.5
Arm abduction/adduction ( $\gamma$ )	30.84 ± 4.25	13.76	30.83 ± 4.82	15.65

Table 3. Linear variables of upper limb movements during a sculling movement

Variable	Upper limb	Mean ± SD	Coefficient of variation (%)	Relative time (%)
Duration of sculling (s)		0.72 ± 0.05	7.32	100
Duration of the first phase of sculling (s)	Right	0.31 ± 0.06	17.96	43
Duration of the second phase of sculling (s)		0.40 ± 0.06	14.43	55.5
Trajectory length of the hand (m)		1.74 ± 0.21	15.15	-
Duration of sculling (s)		0.73 ± 0.05	6.98	100
Duration of the first phase of sculling (s)	Left	0.28 ± 0.05	18.18	38
Duration of the second phase of sculling (s)		0.44 ± 0.05	11.91	60
Trajectory length of the hand (m)		1.64 ± 0.25	15.21	-

\* statistically significant difference  $p \leq 0.05$

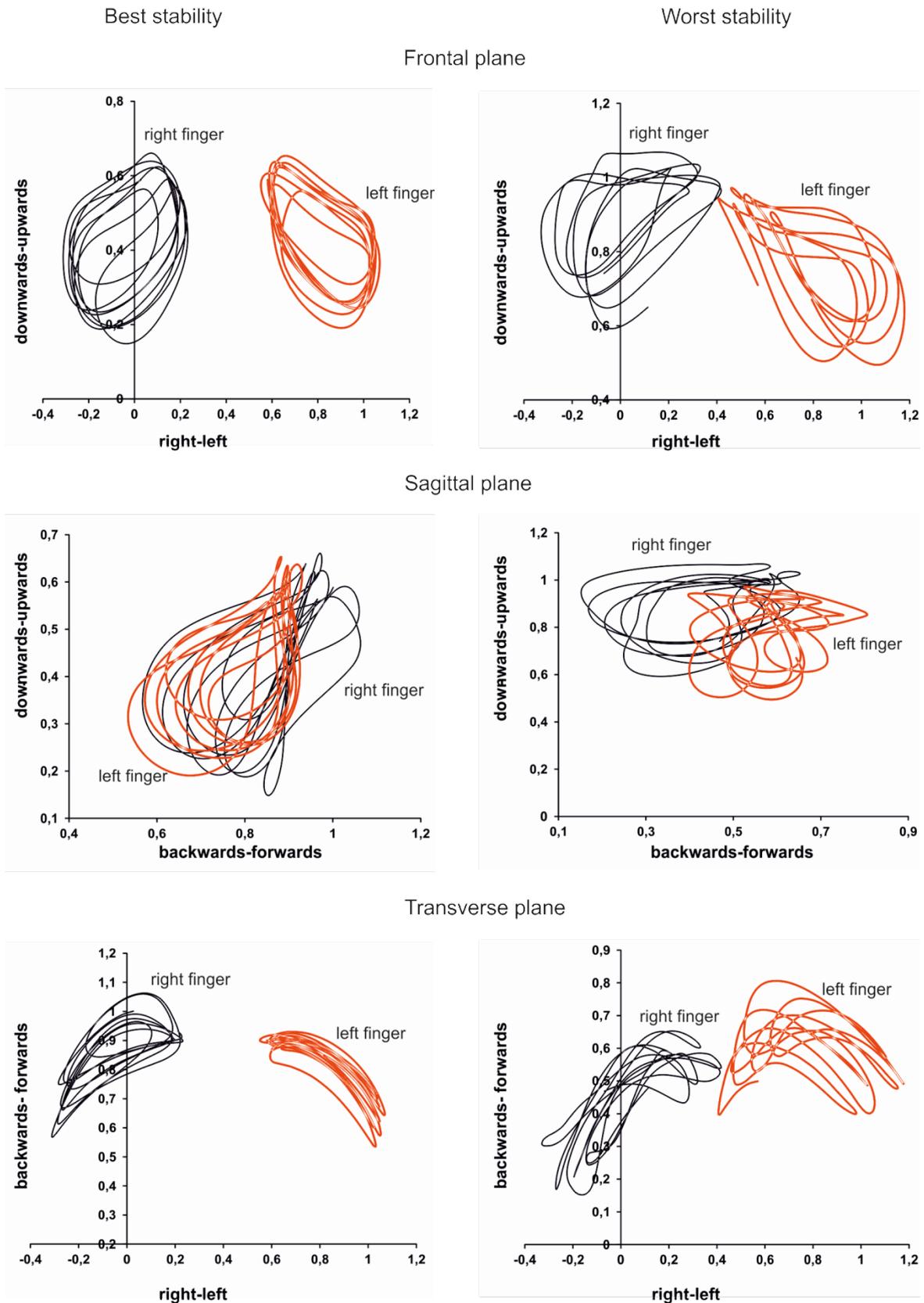


Figure 2. Hand movement trajectory lengths (m) (based on the right and left middle finger marker) for each anatomical plane in the swimmers with the best and worst support scull body stability

present sample of synchronized swimmers showed little variability in sculling movement cycle duration. However, the time of the first and second sculling cycle phases were found to substantially differentiate the swimmers. A comparison of the swimmers with the greatest and least amount of stability indicated that the swimmer with the most sway presented prolonged movement cycle and phase duration. For comparison purposes, the Olympic silver medalists examined by Homma and Homma [13] featured a shorter sculling movement cycle (0.69 s) than the best swimmer in this study, indicating a relationship between scull cycle duration and competitive level. In addition, Rostkowska et al. [21] also demonstrated an association between the duration of the entire movement cycle and performance level, suggesting that swimmers who have trained for a longer period of time and achieved greater success exhibit reduced support scull movement time.

Analysis of the angular kinematics in sculling was delineated to the examined ranges of movement. The greatest range of movement was observed in the adduction and abduction of the forearm. This range of movement was also characterized by the smallest variability among the swimmers. Homma and Homma [15] investigated the minimum and maximum angular values and ranges of movement in synchronized swimming. While their results on wrist joint flexion are congruent with that observed in the present study, a number of differences were found between both studies regarding the movement ranges of the elbow joint. This may be explained by differences in the skill level of the samples, where the elite athletes exhibited greater palmar and dorsal flexion whereas the lower-level swimmers in the present study showed no dorsal flexion [15]. This finding highlights the importance of training hand dorsiflexion, as it likely to influence sculling efficacy.

To our knowledge, no studies have yet analyzed the kinematic factors that affect body stability in synchronized swimming. This is surprising, as judges assess the ability to maintain the non-submerged parts of the body in a stable upright position over the water [17]. We assumed that one valid measure of body stability in support scull may be the displacement and ranges of movement of the pubic symphysis in all three anatomical planes, as this anatomical location is the closest to the body's overall center of gravity. We found that this point on the body was characterized by greater movement variability than the head, although the head marker was characterized by significantly greater displacement in the forward-backward and right-left directions than the pubic symphysis. This may indicate the important role of head movement in correcting the body's stability when upside down underwater. The present findings confirm the importance of fine hand movements in maintaining stability in the vertical position. In particular, we found that an increase in the excursion of the pubic symphysis marker was paralleled with an increased

range of movement of the wrist joint, as was the movement of the body in the right-left and upward-downward directions. Furthermore, a larger sculling angle was associated with greater body displacement in the forward-backward direction. This finding implies that excessive flexion of the upper limbs at the elbow and wrist joints during support scull results in a loss of forward-backward stability. In turn, reduced range of movement of the forearm in relation to the trunk correlated with greater displacement in the right-left direction. These findings were confirmed regardless of whether they were performed by the swimmers featuring the greatest or least stability in the vertical position (albeit the latter was characterized by greater sculling asymmetry).

### Conclusions

The use of a sculling angle, as proposed herein, can serve as a valid measure for dividing the upper limb movements of support scull into phases. Additionally, the trajectory and range of displacement of the pubic symphysis can also quantify body stability in the vertical position. Body stability in the vertical position was associated with the range of movement of the radial wrist joint, angle of forearm adduction, and sculling angle.

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