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Determine the Center of Mass Position in Human Undulatory Swimming: A Static Approach

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Abstract: The knowledge of the actual center of mass (CoM) position enables an estimation of human motion concerning cause-and-effect relations, e.g. using the principles of linear momentum. Although previous analytical methods are able to calculate the CoM, but its precision strongly depends on the quality of the used models and body segments inertial characteristics. Experimental methods provide a more precise location of body's CoM, but often only in one dimension or with inadequate measurement errors. The aim of this study is primary (i) to show an experimental setup to determine swimmer's CoM in 2D (sagittal plane) with small errors of the setup and secondary (ii) to show the location as well as (iii) the variation of swimmer's CoM for different characteristic positions during an undulatory kick cycle. Five female and five male sport students imitated five different positions of an undulatory swimming kick cycle laying sagittal on a triangular platform. The presented method allows to determine the CoM of swimmer's actual position with measurement errors of maximum 4 cm. Horizontal and vertical position of the CoM as well as the Euclidean distance significantly differs from the hip for all participants and during all investigated phases of a kick cycle.

Keywords: Center of Mass Location and Variation, Dolphin Kick, Experimental Determination, Setup Error Analysis and Error Propagation

1. Introduction

Human's center of mass (CoM) is an imaginary point at which the gravitational force acts and its position depends on individual anthropometrics and mass distribution of the body [5], varies during the motion, and can also be located outside the body. At the CoM torques of all masses (due to the gravity) are balanced out. Focusing on the CoM allows to describe dynamics of movement in a reduced and simplified way.

In general, the determination of CoM position can be divided into (i) analytical and (ii) experimental methods. Analytical or geometrical methods calculate the CoM based on models and require both the inertial properties of all individual body segments (e.g., segment mass and segmental center of mass) as well as the location of each segment. The data of the segmental properties is usually provided in tables, often provided by corpses [16]. However, the use of this data and the scaling to the required body dimensions result in errors, e.g. differences between living and deceased tissues [3] or when participants vary compared to the corpses. Using geometric models, body segments are described as geometric shapes (e.g., cylinder, truncated cone) with segment lengths and circumferences obtained from the measured anthropometrics. Different models, e.g. [9] with 15 segments) or [19] with 16 segments, and adjustments [2] allow to calculate the segmental and total CoM using the segmental volumes and densities (e.g., by MRI-scans).

Experimental methods to determine the CoM can be divided into static (e.g., reaction boards) and dynamic (e.g., ground reaction forces) measurements. Reaction boards with one or two scales calculate the generated torques by lever arms and weights [10, 15] and are usable for any rigid posture assumed by a person [4]. However, most of this boards measure only one dimension (e.g., sagittal) of the 3D CoM location. To determine e.g. CoM's frontal and lateral position, the same procedure has to be performed with the participant under the same exact body position. Thus, Basler adapted the setup for larger boards to a triangular platform, supported with scales at two or more points [10]. The corners were supported by contact points and two of the three contact points lay on scales, the third one was elevated for the setup to be level to the ground. The CoM of the participant, lying on the board in a predefined position, can be drawn in 2D by the intersection of two lines using the displayed weights and relations of the two scales.

Using a triangular platform (or other static methods) provides the (static) position of CoM, but not its variation during the motion. In contrast, ground reaction forces [7] provide CoM's displacement and velocity, but not its initial location. Hence, to measure both CoM's position and variation, the movement has to be divided into characteristic phases which can be separately (statically) measured.

In swimming, it is generally accepted to use the CoM to measure swimming velocity [8, 12, 14, 17]. For simplicity, the motion of the hip marker is often used as an approximation. In the four competitive strokes, the velocities of CoM and hip marker follow similar patterns (similar frequency, but different amplitude and phase) within stroke cycles and the hip forward velocity is used as a tool for diagnosing problems. But already in strokes with alternately moving arms and legs and a rotation around the longitudinal axis, the hip marker appears to be accelerating or decelerating more than the CoM. So the hip velocity deviates from true swimming velocity [14]. During underwater undulatory swimming (UUS) both arms are outstretched above the head throughout the cycle. This indicates that the CoM might be located more cranial as compared to the four swimming techniques at the water surface.

The aims of this study are (i) to show an experimental setup to determine swimmer's CoM in 2D (sagittal plane) and (ii) to show the location as well as (iii) the variation of swimmer's CoM for different static characteristic positions during an undulatory kick cycle. Additionally, the measured distance between CoM and hip marker position helps to test whether the hip marker is suitable as a practical and simple substitute of the CoM for the evaluation of swimmer's kinematics.

2. Materials and Methods

A group of ten sport students (five female and five male; age: 22.8 $\pm$ 1.2 years; body weight: 72.6 $\pm$ 5.5 kg and body height: 1.78 $\pm$ 0.04 m) participated in this study to determine the position of the center of mass (CoM) imitating different positions during undulatory swimming.

A triangular platform (side length: a = 1.955 m, b = 1.949 m and c = 2.006 m) was used (Fig. 1) consisting of three aluminium bars and a rigid wooden triangle plank. Each tip of the aluminium construction was further supported by a contact point (diameter: 10 mm). Three scales (MS 01, Beurer; Ulm, Germany; Fig. 1), positioned under the contact points in each corner of the triangle, were tared to zero. The position of swimmer's CoM (X_S, Y_S) – resulting from the scales – is described in detail in Appendix A (Fig. A1):

$$X_S = \frac{m_B(X_B - X_A) + m_C X_C}{m_A + m_B + m_C} \quad (1)$$

$$Y_S = \frac{m_B(Y_B - Y_A) + m_C Y_C}{m_A + m_B + m_C} \quad (2)$$

where m_i represent the measured masses of the scales and (X_i, Y_i) stands for the position of the contact point above the three scales A, B and C.

One kick cycle of UUS was subdivided in a series of five phases of characteristic movement phases in UUS, according to [1]. Because this paper concentrates on the method to determine CoM, the phases are not explicit comparable with the phases used by (high) trained swimmers. Here, the selected phases are only used as an orientation for the swimmers to accurately reproduce the positions within the groups of the tested sport students. The participants lay sagittally on the plank. To position and to establish the same test setup for each participant – as well as to improve the accuracy of the phases – a supporting template for each phase was created (Fig. 1). Their correct body position was tested – and adjusted if necessary – by a camera (LifeCam Studio HD-webcam, resolution: 1920x1080 pixels; Microsoft; Redmond, WA, USA), positioned 3 m above the middle of the triangle.

To control and validate the measured positions of CoM (determined by Eq. (1) and (2)) the camera captured the known positions of reference masses (50 kg and 75 kg; Appendix C). Marker were positioned at the wrist (*Processus styloideus radii*), shoulder joint (*Articulatio humeri*), hip joint (*Trochanter major*), knee joint (*Epicondylus lateralis*), ankle joint (*Malleolus lateralis*), and toe (*Tuberositas ossis metatarsis quinti*). Anthropometrical data such as body length and weight, segmental lengths, and circumferences were obtained. MATLAB 2012a (The MathWorks; Natick, MA, USA) was used for post-processing of the data as well as SPSS 19 (IBM; New York, USA) for all statistical analyses. To compare and normalise the position of the swimmers the positions of all marker (X_i, Y_i) and CoM (X_S, Y_{Si}) were normalised with respect to the hip marker position (hip marker is in the origin of the (x, y)-coordinate system for all swimmers and all positions; Fig. 2) to (x_i, y_i):

$$x_i = X_i - X_{hip} \quad (3)$$

$$y_i = Y_i - Y_{hip} \quad (4)$$

(with the six markers: $i = 1, \ldots, 6$).

The experimental procedures were in accordance with the guidelines of the University of Jena Ethics Committee.

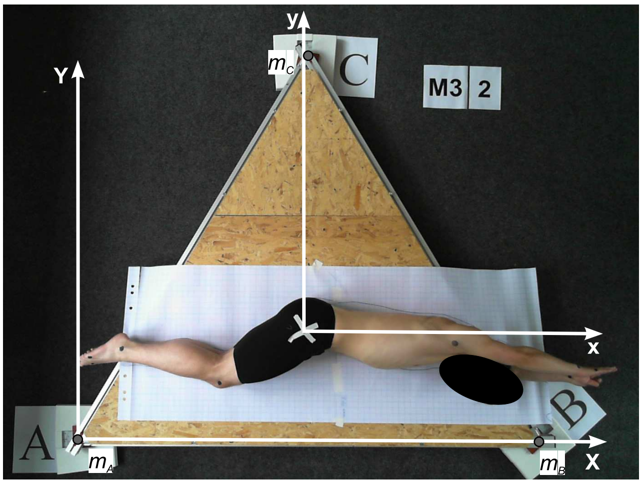

Figure 1. *Top view of the (physical) triangle located on three scales. The masses m_A, m_B and m_C of the scales act in the points A, B and C (gray points). To validate the measured center of mass, during calibration, a camera captured photos of the defined masses on defined locations (Appendix C). A template helps to adjust the swimmer to the correct body position for the actual swimming position. The (X, Y)-coordinate system is defined by the X-axis (by the point A and B) and Y-axis (perpendicular to the X-axis) whereby both have its origin in point A (Appendix A; Fig. A1). The (x, y)-coordinate system is parallel displaced to (X, Y) and has its origin always in swimmer's corresponding hip marker point in each position $((x_{hip}, y_{hip}) \coloneqq (0,0)$; Eq. 3 and 4).*

3. Results

The absolute measurement errors of the setup varies between 3 cm and maximum 4 cm (Tab. B1). The horizontal x_S and vertical y_S position of CoM as well as the Euclidean distance $(x_S^2 + y_S^2)^{0.5}$ with respect to the hip marker (*Trochanter major*) of all subjects and during all phases differ significantly (p< .001; one-sample t-test; Fig. 2). For both groups of female and male subject within the different phases the Euclidean distance and x_S do not vary significantly, however, y_S differs during a kick cycle (p< .05). Mainly the CoM of phase 3 is responsible for this effect (Bonferroni and Tamhane-T2 post-hoc-test). For female, the mean differences between hip and CoM are – depending on the phase – in the range between $x_S = (0.105 \dots 0.129)$ m and $y_S = -(0.043 \dots 0.089)$ m, as well as for male between $x_S = (0.152 \dots 0.172)$ m and $y_S = -(0.040 \dots 0.099)$ m (Tab. 1; Fig. 2). There is no difference between female and male subjects concerning the vertical CoM position y_S, however, the horizontal CoM position x_S (positions 2–4) as well as the Euclidean distance between hip and CoM (positions 2, 3, and 5) significantly differs between both groups (Tab. 1).

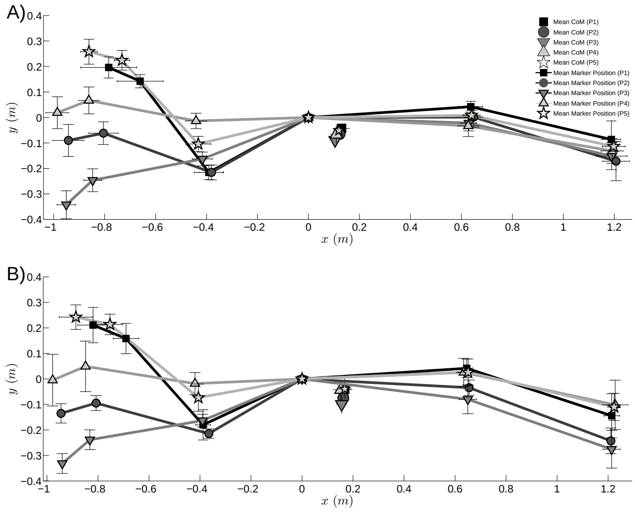

Figure 2. *Mean location of swimmer's center of mass of female (A) and male (B) subjects for the different phases (marker positions (mean ± SD) represented by the stick figures) during undulatory swimming with respect to the hip marker $(x_{hip}, y_{hip}) \coloneqq (0,0)$. Both the center of mass as well as the stick figure phases are colour coded beginning with black (P1) and ending with light gray (P5). The selected phases during a kick cycle are: top kick reversal (P1), middle of the flexion down-kick (P2), bottom kick reversal (P3), middle of the extension up-kick (P4) and almost reaching the top kick reversal (P5), according to [1].*

Table 1. *Center of mass position and (Euclidean) distance from center of mass to the hip marker (mean±SD) for female and male groups during different body positions (Fig. 2B,C) of undulatory swimming. The stars (indicating the p-values) represent significant differences between female and male for each position (Mann–Whitney-U-Test).*

Position	**Subjects**	**Center of mass a (m)**			**Euclidean distance (m)**	
		x_S		y_S	**(Hip marker – CoM)**	
1	female	0.129 ± 0.031		-0.043 ± 0.018	0.138 ± 0.025	**
	Male	0.167 ± 0.029		-0.041 ± 0.041	0.175 ± 0.025	
2	female	0.122 ± 0.019	**	-0.065 ± 0.014	0.139 ± 0.016	**
	Male	0.172 ± 0.018		-0.075 ± 0.020	0.179 ± 0.016	
3	female	0.105 ± 0.011	***	-0.089 ± 0.016	0.138 ± 0.014	***
	male	0.156 ± 0.020		-0.099 ± 0.036	0.188 ± 0.009	
4	female	0.109 ± 0.023	**	-0.067 ± 0.034	0.132 ± 0.021	
	male	0.152 ± 0.029		-0.043 ± 0.039	0.162 ± 0.028	
5	female	0.119 ± 0.019	**	-0.051 ± 0.015	0.131 ± 0.018	***
	male	0.168 ± 0.025		-0.040 ± 0.036	0.176 ± 0.017	

[a] With respect to the hip position: $(x)_{hip}, y_{hip} \coloneqq (0,0)$.

p-values: * (p < .05); ** (p< .01).

4. Discussion

The results of the calibration (Appendix C) show that the location of the measured CoM (by the three scales) and the CoM with defined masses at defined locations observed by the camera does not differ significantly. Small image distortions using the camera might result in slight differences between the CoM measured by the scales vs. the CoM measured by the camera, which can explain the slightly increasing differences for larger y_S-values (systematic trend; Fig. C1). In contrast to Basler's method [10] this method to determine the CoM (Equations (1) and (2); Fig. A1) can be used with an arbitrary triangle which not has to be an equilateral triangle. Subsequently, we present a method to directly calculate the two-dimensional CoM in Cartesian coordinates only based on the three readings of the scales as well as their respective relative positions. Hence, the errors of the setup using Equations (2) and (3) are small and in a range of 3-4 cm (using linear error propagation; Appendix B) and consist of similar ratios according to the errors of the scales Δm_i and to the errors of the location of the corner points $(\Delta x_i, \Delta y_i)$. Here, we only used commercial scales (Δm_i = 0.25 kg) which can be easily replaced, e.g. by more sensitive and accurate force plates to further reduce CoM's error.

As expected, the determined CoM is located cranial and ventral of the hip marker for each tested participant. The horizontal shift is due to the outstretched arms in front of the head and the vertical (negative) shift can be explained that the ventral parts dominate during a kick cycle [11,13]. Even if the CoM is not directly located on the presented stick figures (Fig. 2), it does not necessarily imply that the CoM is located outside the human body. The stick figures (linear connection between two marker points) are only a simplification of human body and neglect the real proportions of the human body. Because the present study focused on the 2D determination of the CoM the third component of CoM (medial/lateral) is missing. Assuming a sufficient symmetrical physique it can be expected that CoM is located centrally within the frontal plane during UUS. In contrast, in strokes where the arms move alternately CoM can vary more about the central position [14].

The results of this study show that the position of the hip marker significantly differs compared to the CoM during all tested phases in UUS (two-tailed t-test against value 0; where (0,0) represents the hip position), similar to [6] who indicated for crawl swimming that the hip marker only reflects the horizontal displacement of CoM. The differences in x_S between female and male can be generally explained by a different body mass distribution. To reduce the effect of the height it was disposed to choose participants with similar body heights (1.70–1.80 m for female and 1.75–1.85 m for male participants).

The selected predefined positions which reflect one UUS kick cycle based on [1] who only used one elite level male swimmer. Hence, it could be assumed that these positions might not reflect the exact posture which would be adopted by all the participants or even other elite swimmers in real UUS. As the presented method is easy to handle, for future, swimmer can adjusted to their individual phases/positions according their previous captured swimming kinematics during UUS.

As soon as there is a difference between CoM (gravitational point of action) and CoV (center of volume; volume point of action) a torque results. Swimmer's CoM is substantially affected by breathing (full or empty lungs) whereas the position of the CoV is hardly affected. Here, we estimate only the position of the CoM.

5. Conclusion

Finally, this experimental method to determine swimmer's CoM easily allows to validate CoM values calculated by (different) models. This helps to check the quality of the modeled CoM for individual swimmers and assesses its usability.

This is particularly important to accurately verify the appropriateness of the use of the hip marker as a practical and simple substitute of the CoM for the evaluation of swimmer's kinematics, particularly intra-cyclic speed fluctuations.

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Appendix

Appendix A: Determination of swimmer's center of mass

The measure method to calculate the center of mass dependent on the relation of masses acting in the corners is based on a massless triangle (Fig. A1). At the corner points A, B and C there are the masses m_A, m_B and m_C. The triangle including these three masses is balanced in the center of mass (S). In this case relations of the length are:

$$\frac{h_1}{h_2} = \frac{m_A+m_B}{m_C};\ \frac{g_1}{g_2} = \frac{m_B+m_C}{m_A};\ \frac{l_1}{l_2} = \frac{m_A+m_C}{m_B} \quad (5)$$

and

$$\frac{c_1}{c_2} = \frac{m_B}{m_A};\ \frac{a_1}{a_2} = \frac{m_C}{m_B};\ \frac{b_1}{b_2} = \frac{m_A}{m_C} \quad (6)$$

Using the relations (5) and (6) as well as with the assumption that A represents the origin of the coordinate system (according to Fig. 1) the center of mass $\vec{S} = (X_S, Y_S)$ is:

$$\vec{S} = \begin{pmatrix} X_S \\ Y_S \end{pmatrix} = \frac{m_B\begin{pmatrix} X_B - X_A \\ Y_B - Y_A \end{pmatrix} + m_C\begin{pmatrix} X_C \\ Y_C \end{pmatrix}}{m_A+m_B+m_C} \quad (7)$$

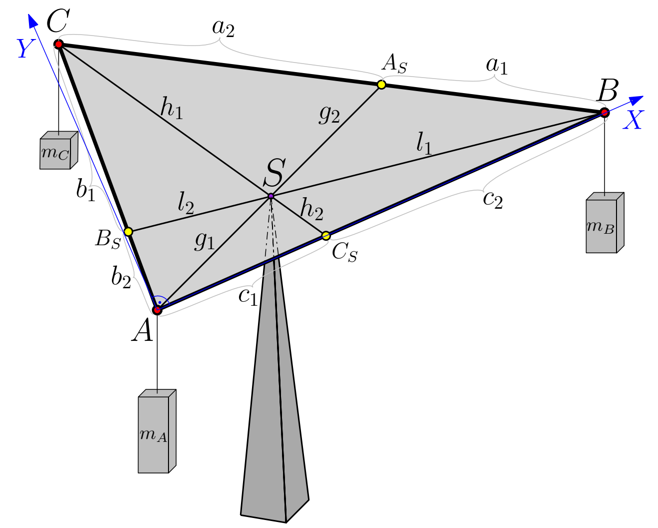

Figure A1. *Schematic overview about the measure method (not according to scale or to relations). The (arbitrary) triangle including the three masses at the corner points A, B and C is balanced in the center of mass (S). The three lines g, l, and h are defined by the center of mass S and the corner points A, B and C, respectively. The (X,Y)-coordinate system (Fig. 1) has its origin in point A, the X-axis is defined by the points A and B and the Y-axis is perpendicular to the X-axis (adapted from [18]).*

Appendix B: Error analysis and error propagation

A linear error propagation was used to estimate on the errors of the center of mass values due to measure errors. Thereby, the errors ΔX_S and ΔY_S are:

$$\Delta X_S = \left|\frac{\partial X_S}{\partial X_A}\right| \Delta X_A + \left|\frac{\partial X_S}{\partial X_B}\right| \Delta X_B + \left|\frac{\partial X_S}{\partial X_C}\right| \Delta X_C + \left|\frac{\partial X_S}{\partial m_A}\right| \Delta m_A + \left|\frac{\partial X_S}{\partial m_B}\right| \Delta m_B + \left|\frac{\partial X_S}{\partial m_C}\right| \Delta m_C = \left|-\frac{m_B}{m_A+m_B+m_C}\right| \Delta X_A + \left|\frac{m_B}{m_A+m_B+m_C}\right| \Delta X_B + \left|\frac{m_C}{m_A+m_B+m_C}\right| \Delta X_C + \left|-\frac{m_C X_C - m_B(X_A - X_B)}{(m_A+m_B+m_C)^2}\right| \Delta m_A + \left|\begin{matrix}-\dfrac{X_A - X_B}{m_A+m_B+m_C} \\ -\dfrac{m_C X_C - m_B(X_A - X_B)}{(m_A+m_B+m_C)^2}\end{matrix}\right| \Delta m_B + \left|\frac{X_C}{m_A+m_B+m_C} - \frac{m_C X_C - m_B(X_A - X_B)}{(m_A+m_B+m_C)^2}\right| \Delta m_C \quad (8)$$

$$\Delta Y_S = \left|\frac{\partial Y_S}{\partial Y_A}\right| \Delta Y_A + \left|\frac{\partial Y_S}{\partial Y_B}\right| \Delta Y_B + \left|\frac{\partial Y_S}{\partial Y_C}\right| \Delta Y_C + \left|\frac{\partial Y_S}{\partial m_A}\right| \Delta m_A + \left|\frac{\partial Y_S}{\partial m_B}\right| \Delta m_B + \left|\frac{\partial Y_S}{\partial m_C}\right| \Delta m_C = \left|-\frac{m_B}{m_A+m_B+m_C}\right| \Delta Y_A + \left|\frac{m_B}{m_A+m_B+m_C}\right| \Delta Y_B + \left|\frac{m_C}{m_A+m_B+m_C}\right| \Delta Y_C + \left|-\frac{m_C Y_C - m_B(Y_A - Y_B)}{(m_A+m_B+m_C)^2}\right| \Delta m_A + \left|-\frac{Y_A - Y_B}{m_A+m_B+m_C} - \frac{m_C Y_C - m_B(Y_A - Y_B)}{(m_A+m_B+m_C)^2}\right| \Delta m_B + \left|\frac{Y_C}{m_A+m_B+m_C} - \frac{m_C Y_C - m_B(Y_A - Y_B)}{(m_A+m_B+m_C)^2}\right| \Delta m_C \quad (9)$$

with the errors of the positions of the corner points ($\Delta X_A = \Delta X_B = \Delta X_C = 0.02$ m) as well as the errors due to the mass measurements ($\Delta m_A = \Delta m_B = \Delta m_C = 0.25$ kg). Hence, each measured CoM value is connected with its corresponding error (Tab. B1).

Table B1. *Center of mass position (horizontal x_S and vertical y_S component) of each subject for all positions with its corresponding measurement errors Δx_S and Δy_S.*

Subject	**Sex**	**Position 1** $x_S \pm \Delta x_S$ **(m)**	**Position 2** $x_S \pm \Delta x_S$ **(m)**	**Position 3** $x_S \pm \Delta x_S$ **(m)**	**Position 4** $x_S \pm \Delta x_S$ **(m)**	**Position 5** $x_S \pm \Delta x_S$ **(m)**
1	female	0.138 ± 0.042	0.128 ± 0.041	0.102 ± 0.040	0.097 ± 0.041	0.122 ± 0.042
2	female	0.092 ± 0.039	0.092 ± 0.038	0.089 ± 0.038	0.080 ± 0.040	0.089 ± 0.038
3	female	0.111 ± 0.042	0.122 ± 0.040	0.101 ± 0.039	0.107 ± 0.039	0.118 ± 0.040
4	female	0.175 ± 0.041	0.144 ± 0.041	0.119 ± 0.041	0.140 ± 0.040	0.140 ± 0.042
5	female	0.132 ± 0.041	0.123 ± 0.042	0.111 ± 0.040	0.122 ± 0.040	0.128 ± 0.041
6	male	0.157 ± 0.040	0.161 ± 0.039	0.175 ± 0.038	0.162 ± 0.040	0.179 ± 0.040
7	male	0.162 ± 0.041	0.168 ± 0.039	0.161 ± 0.038	0.165 ± 0.038	0.179 ± 0.039
8	male	0.140 ± 0.041	0.137 ± 0.039	0.140 ± 0.038	0.124 ± 0.039	0.149 ± 0.040
9	male	0.160 ± 0.040	0.156 ± 0.038	0.129 ± 0.038	0.121 ± 0.041	0.135 ± 0.038
10	male	0.217 ± 0.040	0.187 ± 0.040	0.172 ± 0.039	0.190 ± 0.039	0.195 ± 0.040
Subject	**Sex**	**Position 1** $y_S \pm \Delta y_S$ **(m)**	**Position 2** $y_S \pm \Delta y_S$ **(m)**	**Position 3** $y_S \pm \Delta y_S$ **(m)**	**Position 4** $y_S \pm \Delta y_S$ **(m)**	**Position 5** $y_S \pm \Delta y_S$ **(m)**
1	female	-0.018 ± 0.031	-0.042 ± 0.030	-0.075 ± 0.030	-0.042 ± 0.030	-0.037 ± 0.030
2	female	-0.069 ± 0.030	-0.068 ± 0.029	-0.083 ± 0.029	-0.083 ± 0.030	-0.052 ± 0.029
3	female	-0.046 ± 0.031	-0.082 ± 0.030	-0.116 ± 0.029	-0.085 ± 0.029	-0.075 ± 0.030
4	female	-0.038 ± 0.030	-0.064 ± 0.031	-0.093 ± 0.030	-0.022 ± 0.029	-0.051 ± 0.031
5	female	-0.043 ± 0.031	-0.067 ± 0.031	-0.078 ± 0.030	-0.103 ± 0.030	-0.039 ± 0.030
6	male	-0.020 ± 0.031	-0.064 ± 0.030	-0.038 ± 0.029	0.015 ± 0.030	-0.019 ± 0.030
7	male	-0.014 ± 0.031	-0.101 ± 0.030	-0.098 ± 0.029	-0.039 ± 0.029	-0.052 ± 0.030
8	male	-0.001 ± 0.031	-0.077 ± 0.030	-0.123 ± 0.029	-0.034 ± 0.029	-0.057 ± 0.030
9	male	-0.089 ± 0.030	-0.085 ± 0.029	-0.129 ± 0.029	-0.083 ± 0.031	-0.081 ± 0.029
10	male	-0.081 ± 0.030	-0.049 ± 0.031	-0.108 ± 0.030	-0.074 ± 0.030	0.011 ± 0.030

Appendix C: Calibration of the setup

To control the setup two different reference masses (50 kg and 75 kg) were positioned at different locations on the triangle. Its positions were captured with the camera positioned 3 m above approximately the middle of the triangle (Fig. 1). Both methods to determine the CoM during UUS (scales vs. camera) show matching CoM position (Fig. C1). There are only slight differences (in the range of 0.5–3 cm), which were probably due to the distortion of the camera.

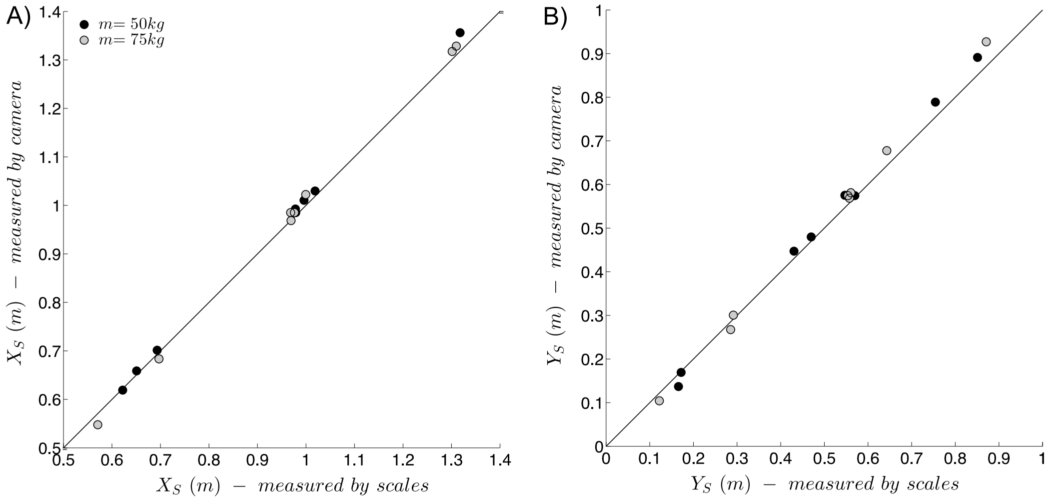

Figure C1. *Comparison of the center of mass coordinates X_S (A) and Y_S (B) – for two calibration masses (50 kg and 75 kg; according to the swimmer's weights) located on the triangle – between the two different methods: (i) using the three scales (abscissa) in comparison to (ii) using a camera (ordinate). The center of the triangle is represented by X_S = 1 m and Y_S = 0.58 m (Fig. 1). The solid lines both represent the identity (with a slope of 1). For both directions (X_S and Y_S) there is a trend that for larger values the camera method overestimate the values.*

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