The Relationship between Buoyancy and Airborne Weight in Synchronized Swimmers

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(abstract)

The purpose of this study was to examine the relationship between the buoyancy of synchronized swimmers and the airborne weight of basic positions. Whole-body volume, buoyancy, underwater weight, and airborne weight at 12 levels in basic positions were measured for eight female synchronized swimmers (15.6 ± 2.98 years, 1.60 ± 0.05 m, 52.7 ± 4.40 kg). The main results were as follows. The surplus buoyancy of synchronized swimmers was 2.19 ± 1.78 kgf. In the upright position, the airborne weight of double arm changed from 8.58 ± 0.63 kgf (16.3%) at the shoulders to 28.44 ± 2.99 kgf (53.9%) at the mid-pelvis. In the inverted position, the airborne weight of double leg changed from 3.77 ± 0.97 kgf (7.1%) at the kneecap to 7.77 ± 0.95 kgf (14.7%) at the crotch level. In the horizontal position, the airborne weight for the ballet leg double changed from 7.18 ± 0.94 kgf (13.6%) at the mid-thigh to 12.95 ± 1.72 kgf (24.6%) at the crotch level. Although there was no effect from greater surplus buoyancy on positions with a large airborne weight, swimmers with greater buoyancy could more efficiently hold parts of the body above the water in positions with a small airborne weight. It is important to increase supporting force via propulsive techniques to support large airborne weights.

Key words: Synchronized swimming, Surplus buoyancy, Loads above the water surface, Airborne weight

I. INTRODUCTION

Synchronized swimming is a scored point competition, in which the precision of movement in unison, one with the other, and the accompaniment above and below the water surface are required. Free Routine is scored by three judging panels in terms of Execution, Artistic Impression, and Difficulty. In judging Execution, a maximum body height is required during each performance, which is determined on the basis of the relationship between the water level and the position of the body. For example, the vertical height in an inverted position with both legs together is scored as 8.5 points if the water level is at the mid-thigh and as 5.5 points if the level is at the kneecap (FINA 3). Meanwhile, the Difficulty panel assigns higher difficulty values depending on the airborne weight that is maintained during the performance. For example, elevating both legs in a vertical position has a higher difficulty level than elevating one leg, resulting in a higher score. The height and airborne weight are important benchmarks used by judges in the scoring criteria. Thus, to achieve a high score, the swimmer has to raise their body as high as possible and support a large body volume above the water surface for a long period.

Synchronized swimming performances last a maximum of 4.5 min, and most of that time is spent with the majority of the trunk immersed in water. If a portion of the body is lifted out of water, buoyancy decreases in proportion to the volume raised above the water level. Thus, maintenance of posture requires the swimmer to obtain a supporting force equivalent to the decrease in buoyancy. In synchronized swimming, an upward supporting force is achieved via the propulsive techniques of sculling and the eggbeater kick to hold the body...
above water, enabling various expressive movements to be performed. Swimmers with greater buoyancy require less supporting force to perform a particular movement than those with less buoyancy, and these swimmers are capable of more efficient, stable motions. Consequently, buoyancy is an important factor for synchronized swimmers.

Buoyancy is dependent on specific gravity. The human body stores air within the lungs, which can therefore change in volume. The specific gravity of the body can be reduced by breathing deeply, which expands the chest and introduces a large quantity of air into the lungs. Nygren-Bonnier et al.\(^9\) reported that adding breathing exercises to ordinary swimming training resulted in chest expansion and increases in lung volume and buoyancy. Sasaki et al.\(^10\) compared breathing and circulatory function among water polo players during eggbeater kicking and cycling, noting that the breathing frequency was lower and the tidal volume was significantly greater during eggbeater kicking. In addition, it has been suggested that water polo players attempt to maintain their upper bodies above the water level both via leg movements and by increasing buoyancy using breathing techniques. Therefore, increasing lung capacity and torso volume is important for increasing buoyancy. In addition, body shapes characterized by a larger underwater torso section and thinner limbs have a smaller specific gravity, and they are considered to benefit more from buoyancy.

Hall\(^4\) kinematically analysed the supporting scull motion in the vertical position in three world-champion American national team synchronized swimmers, revealing that the swimmer with the highest body fat percentage and the thinnest legs had the longest scull time and a horizontal stroke plane. This result suggests that a higher body fat percentage and lighter portions held above water contribute to easing the exertion of upward supporting force. The only other previous study that measured the loads above water in various positions in synchronized swimmers was reported by Homma\(^7\).

In this context, it would be possible to more efficiently raise the body high above water if the loads above the water surface are smaller and the portion of the body that is underwater is more buoyant. However, no studies addressing the loads above the water surface and buoyancy have been published, and the relationship between the two is unclear. In addition, although the height scoring scale in synchronized swimming is based on the water level on the body, few studies have experimentally verified a correlation with airborne weight.

Thus, the purpose of this study was to examine the relationship between the buoyancy of synchronized swimmers and the airborne weight of basic positions like Eggbeater kick, Boost, Vertical, Fishtail, Ballet leg and Ballet leg double positions. Ordinarily, “airborne weight” as used in synchronized swimming competitions indicates the weight raised above water for support when a portion of the body is raised out of water, and “loads above the water surface” has the same meaning. In this study, the terminology “airborne weight” is used.

II. METHODS

A. PARTICIPANTS

Eight female synchronized swimmers with national competition experience participated in the study. The study was approved by the ethics committee of the Faculty of Health and Sport Sciences at the University of Tsukuba and complied with the Declaration of Helsinki. Written informed consent was obtained from all swimmers prior to commencing the study. The eight swimmers were on average 15.6 ± 2.98 years old, 1.60 ± 0.05 m in height, and 52.7 ± 4.40 kg in weight, and they had a mean percentage body fat of 22.9% ± 1.01%. Body weight and percentage body fat were measured using a body composition measurement device (Inbody 430, Kabushiki Kaisha Sports Style, Japan).

B. MEASURING BUOYANCY

An acrylic plate water tank (height: 1.17 m, width: 1.0 m, depth 1.0 m) was used for all measurements. The water temperature was 27.5°C, and the water density was 996.373 kg/m\(^3\)\(^1\).

B-1. WHOLE-BODY VOLUME

The amount of water displaced when the entire body was immersed in the tank was used to estimate the whole-body volume. The increase in the water level was measured using
scale graduations affixed to the water tank. In addition, because the water surface was unstable, a video camera was installed at the same height as the graduated water level markings. Video was recorded for 5 s after the water surface stabilized, and the stable value was measured. To facilitate whole-body immersion at maximum inspiration, two 5 kg dumbbells were placed in the water tank, and the swimmers were instructed to use the dumbbells to submerge their entire bodies. The water temperature was set to be the same as that of an indoor pool to match the conditions of the airborne weight measurement. In this study, the difference between whole-body buoyancy and body weight was defined as surplus buoyancy.

C. AIRBORNE WEIGHT MEASUREMENT

Measurements were taken in an indoor 50 m pool with a depth of 3.8 m. The water temperature was 27.5°C, and the water density was 996.373 kg/m$^3$\(^1\).

C-1. MEASUREMENT POSITIONS AND WATER LEVEL

We measured the underwater weight when the whole body was immersed and in positions in which portions of the body were raised out of water. Three body positions in which a portion of the body was lifted above water corresponding to the basic or most used motions of synchronized swimming were used, namely an upright position corresponding to the eggbeater kick and the boost (boost means an explosive movement performed by raising the upper body high over water using an eggbeater kick and breast kick), inverted positions and horizontal positions corresponding to figures (figures mean the technical skills which composed of basic positions and movements). The airborne weights at a total of 12 water levels were measured (Fig. 1). All measurement positions were confirmed by an expert with FINA official certified judge qualification. The water levels were set according to the height scale indicated in the FINA Synchronized Swimming Manual (FINA\(^2\)). The airborne weight was measured at the water level of the shoulders, mid-bust, and under the bust in an upright position with both arms raised (eggbeater kick double arm); at the waist and mid-pelvis in an upright position with both arms raised (boost double arm); at the kneecap, mid-thigh, and upper thigh in the inverted position with both legs raised (vertical double leg); at the crotch level in the inverted position with one leg raised (fishtail); at the crotch level in the horizontal position with one leg raised (ballet leg single); and at the mid-thigh and crotch level in the horizontal position with both legs raised (ballet leg double). The measurements taken with portions of

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**Fig. 1.** Water level of basic body positions for airborne weight measurement. (Left) upright position corresponding to the eggbeater kick and the boost by raising the upper body high over water, (Center) inverted position and (Right) horizontal positions corresponding to figures.
the body raised above water were performed by defining the water level as if the water surface cut across the body surface.

C-2. MEASUREMENT PROCEDURE

Airborne weight at 12 levels in different positions and the underwater weight were measured using a digital force gauge (FGX, Nidec-Shimpo Corporation, Japan).

The underwater weight measurement was performed by hanging a digital force gauge on a pole, attaching a rope to the digital force gauge, and adjusting the position of the pole so that the entire body was submerged underwater (Fig. 2). To stabilize the swimmer’s body position in water, a 3.2 kg weight was tied around the waist. This was performed under maximum inspiration. The measurement was taken for 3 s while the body was at rest and the water surface was stable. The underwater weight was sampled at 50 Hz using the digital force gauge, and an average of 50 continuously stable values during a 3 s period was used. The weight of the weights and rope measured under submerged conditions identical to the actual measurements was subtracted from this value, resulting in a corrected value representing the weight during full-body immersion (i.e., the underwater weight value).

The airborne weight measurement was performed by installing the digital force gauge on a pole with both ends secured to stands, attaching a rope to the digital force gauge, and stabilizing the bodies of the subjects at the specific water levels (Fig. 3). The various body sections of the swimmers were marked prior to the measurement with tape to permit the water level for measurement to traverse the water surface at each body site. The swimmers assumed the specific positions at maximum inspiration, and the airborne weight was measured for a 5 s period after the rope stopped swaying. Recordings were taken 50 Hz using the digital force gauge, and the average of 50 continuously stable values within a 5 s period was used. The measurement was taken three times for each position, and the average of the values was used. To stabilize the positions of the swimmers, the swimmers held a 1.3 kg weight during the inverted position. The weight of the rope and the weight that was tied around the hips of the swimmer were subtracted from the measured value when the entire body was immersed in water in the state of maximum inspiration. The resulting value was the airborne weight in each position. The weight obtained by the digital force gauge was expressed in kg, but the density of water is close to 1; thus, the obtained values were converted to body volume (m³). Furthermore, the airborne weight indicates the decrease in buoyancy; therefore, consistent units of kgf were used.

Fig. 2. Underwater weight measurement.
The underwater weight was measured by hanging a digital force gauge on a pole, attaching a rope to the digital force gauge, and adjusting the position of the pole so that the entire body was submerged underwater.
D. STATISTICAL ANALYSIS

SPSS Statistics Version 21.0 for Windows was used for statistical analysis. The Shapiro–Wilk test was used to test normality, and if normality was not confirmed, analyses were performed via a nonparametric method. We used Spearman’s rank correlation coefficient to analyse the correlation between surplus buoyancy and airborne weight for representative positions. The significance threshold was 5% for all tests.

III. RESULTS

The results for whole-body volume, underwater weight, buoyancy, and surplus buoyancy for all swimmers are shown in Table 1. The average whole-body volume, underwater weight, and surplus buoyancy for the eight swimmers were $0.055 \pm 0.005 \text{ m}^3$, $-1.10 \pm 1.15 \text{ kg}$, and $2.19 \pm 1.78 \text{ kgf}$, respectively. The percentage (%) body weight and the airborne weight (kgf) for each water level in each position are shown in Table 2.

In the upright position, the airborne weights for the eggbeater kick double arm were $8.58 \pm 0.63 \text{ kgf (16.3%)}$ at the shoulders, $15.68 \pm 1.73 \text{ kgf (29.7%)}$ at the mid-bust, and $18.95 \pm 1.87 \text{ kgf (35.9%)}$ at the under-bust. The airborne weights for the boost were $23.91 \pm 1.62 \text{ kgf (45.3%)}$ at the waist and $28.44 \pm 2.99 \text{ kgf (53.9%)}$ at the mid-pelvis.

In the inverted position, the airborne weights for the vertical double leg were $3.77 \pm 0.97 \text{ kgf (7.1%)}$ at the kneecap, $23.91 \pm 1.62 \text{ kgf (45.3%)}$ at the shoulders, $15.68 \pm 1.73 \text{ kgf (29.7%)}$ at the mid-bust, and $18.95 \pm 1.87 \text{ kgf (35.9%)}$ at the under-bust. The airborne weights for the boost were $23.91 \pm 1.62 \text{ kgf (45.3%)}$ at the waist and $28.44 \pm 2.99 \text{ kgf (53.9%)}$ at the mid-pelvis.
5.58 ± 0.91 kgf (10.6%) at the mid-thigh, and 9.22 ± 0.88 kgf (17.5%) at the upper thigh. The airborne weight for the fishtail was 7.77 ± 0.95 kgf (14.7%) at the crotch level.

In the horizontal position, the airborne weight for the ballet leg single was 7.77 ± 0.81 kgf (14.7%) at the crotch level. The airborne weights for the ballet leg double were 7.18 ± 0.94 kgf (13.6%) at the mid-thigh and 12.95 ± 1.72 kgf (24.6%) at the crotch level.

The results for the correlation between surplus buoyancy and airborne weight in each position are shown in Table 3. In the upright position, the correlation for the eggbeater kick double arm at the shoulders was \( r = -0.850 \) (\( p < 0.01 \)). In the inverted position, the correlation for the vertical double leg at the kneecap was \( r = -0.783 \) (\( p < 0.05 \)), and at the mid-thigh, the correlation was \( r = -0.711 \) (\( p < 0.05 \)). In the horizontal position, the correlation for the ballet leg single at the crotch level was \( r = -0.786 \) (\( p < 0.05 \)), and for the ballet leg double at the mid-though, the correlation was \( r = -0.922 \) (\( p < 0.01 \)).

**IV. DISCUSSION**

**A. SURPLUS BOUYANCY**

The surplus buoyancy averaged 2.19 ± 1.78 kgf. However, with a high value of 4.99 kgf and a low value of 0.20 kgf, large individual differences were observed among the swimmers. In addition, we observed differences in surplus buoyancy despite nearly identical heights and weights among the participants. For example, swimmers B and F had identical heights of 1.65 m and nearly identical weights of 57.0 and 58.0 kg, respectively, but their surplus buoyancies were 2.78 and 4.78 kgf, respectively, representing a difference of 2.0 kgf. Furthermore, swimmers C and H were both 1.58 m tall, and they had nearly identical weights of 51.3 and 51.8 kg, respectively. Nevertheless, their surplus buoyancies were 2.50 and 4.99 kgf, respectively, representing a difference of 2.49 kgf. These findings indicate that despite identical heights and weights, swimmers F and H would need to support an excess load of 2.0–2.5 kgf when assuming the same position.

The individual differences in surplus buoyancy are reported to be due to differences in body size, lung capacity and body composition. Analysis of the correlation between the measured data in Table 1 and surplus buoyancy using Spearman rank correlation coefficient showed a significant correlation for Buoyancy \( r = 0.530 \) (\( p < 0.05 \)) and age \( r = -0.453 \) (\( p < 0.05 \)). The respiratory function and the development of the trunk by maturation may be possibilities which affect surplus buoyancy. Meanwhile, there was no significant correlation for weight.
correlation between surplus buoyancy and body height $r = 0.198$, body weight $r = 0.088$. Thus, determining the surplus buoyancy of a swimmer can be considered impossible using body height and body weight alone.

B. THE AIRBORNE WEIGHT IN EACH POSITION

A prior study (Homma7)) measuring the airborne weight of three athletes (height: 1.55 ± 0.003 m; weight: 52.4 ± 0.4 kg) reported values of 29.8 ± 0.1 kgf for the eggbeater kick double arm at the mid-pelvis, 9.1 ± 0.6 kgf for the vertical double leg at 10–17 cm above the knee (upper thigh), 6.6 ± 1.0 kgf for the fishtail at the crotch level, 8.5 ± 0.4 kgf for the ballet leg single at the crotch level, and 19.1 ± 0.9 kgf for the ballet leg double at the crotch level. In comparison, our results were 6.2 kg lower for the ballet leg double at the crotch level. The reason why the big difference was seen from the previous research is presumed to be that the volume of the upper body floated out of the water surface was different when setting the water level of the crotch at the ballet leg double position. In this study, the upper body was mostly immersed in the water when setting the water level, so it is considered that the airborne weight was lower. We did not observe any significant differences in airborne weight between swimmers and between positions suggested that differences in body shape affected the airborne weight.

Maintaining various positions in synchronized swimming requires obtaining an upward supporting force via sculling with the arms or using the eggbeater kick or kicking with the legs. According to Homma et al. 8), the fluid forces exerted per cycle of sculling using one arm as measured using a pressure distribution measurement method with female synchronized swimmers were 41.3 N for a flat scull and 67.7 N for a supporting scull. Similarly, according to Tsunokawa11), the fluid force exerted per cycle of eggbeater kicking by one leg as measured using a pressure distribution measurement method with male water polo players was 45.1–70.7 N. In reality, sculling and the eggbeater kick are performed with both arms and both legs; thus, simply doubling these values results in an estimated 82.6 N from flat sculling to maintain a horizontal position, 134.4 N from support sculling used in maintaining an inverted position, and 90.2–141.4 N for treading water. In addition, Yanagi et al. 12) measured the force in the vertical direction from the legs alone resulting from 5 s of a full-force eggbeater kick in female water polo athletes (n = 15, average weight: 60.2 kg) and reported values of 60–120 N. Hara et al. 6) reported that the force in the vertical direction from the legs alone resulting from the eggbeater kick in female water polo athletes averaged 7.2 kgf. Comparing these prior results with the airborne weights obtained in this study, the fluid force from the flat scull according to Homma et al.8) could potentially support the ballet leg single at the crotch level and the ballet leg double at the mid-thigh. The ballet leg double at the crotch level is not included in the height scoring scale, indicating that this is recognized as a water level that cannot be maintained using the flat scull. Consequently, it is conceivable that the fluid force for flat sculling as calculated using a pressure distribution measurement method and the results of this study are reasonable. The fluid forces for the supporting scull according to Homma et al. 8) are capable of supporting the vertical double leg at the upper thigh and the fishtail at the crotch level, and these are positions that are frequently used during performances. The fluid force values for the eggbeater kick according to Tsunokawa 11) were obtained in male water polo athletes, and although they cannot be directly compared with values obtained for female synchronized swimmers studied in this study, the values were sufficient to support the eggbeater kick double arm at the shoulders, but insufficient to maintain the move at the mid-bust and under-bust. Furthermore, the vertical forces during the eggbeater kick for female water polo athletes indicated by Yanagi et al. 12) could support the eggbeater kick double arm at the shoulders, but it is insufficient to support the swimmer at the mid-bust and under-bust.

C. THE RELATIONSHIP BETWEEN AIRBORNE WEIGHT AND DIFFICULTY PANEL SCORES

The magnitude of the airborne weight that is maintained is reflected in the scores given by the difficulty panel (FINA 3)). The results of this study indicated that airborne weight increases even by a slight increase of the water level at the torso or thigh. The torso has a greater circumference than the
limbs; thus, airborne weight becomes much greater with a height increase of just a few centimetres. This supports a marked increase in difficulty when attempting to hold the body high above water. In addition, from the result that the airborne weight of the double leg was greater than that of the single leg, it is clear that movement with both legs in a hybrid figure (hybrid figure means a figure of mixed origin or composition) require higher supporting force and skills than one-leg movements. Although a sustained airborne weight is cited as an important element of difficulty scoring in the FINA rules, there is not set scoring criteria. In the future, there is a need for further study of airborne weight and creating a scoring criteria for sustained airborne weight.

D. RELATIONSHIP BETWEEN INDIVIDUAL SURPLUS BUOYANCY AND AIRBORNE WEIGHT IN EACH POSITION

We detected a significant relationship between airborne weight and individual surplus buoyancy for the eggbeater kick double arm at the shoulders, vertical double leg at the knee-cap and mid-thigh, ballet leg single at the crotch level, and ballet leg double at the mid-thigh. These results indicate that in positions with a low airborne weight, or swimmers with greater surplus buoyancy have a lower airborne weight. This indicates that it is advantageous for the portions immersed in water to be more buoyant.

Synchronized swimming involves performances lasting 2–4.5 min, during which the arms and legs are raised above water with the torso normally submerged. Consequently, a greater torso volume immersed in water leads to greater buoyancy. Nygren-Bonnier et al.9 revealed that maximum lung capacity can be increased via respiratory exercise training, and as a result, the chest expands and buoyancy increases significantly. Furthermore, a study by Sasaki et al.10 suggested that during the eggbeater kick, water polo athletes attempt to maintain their upper bodies above water both through leg movements and by increasing buoyancy through breathing; therefore, increasing lung capacity can be considered as an important point for enhancing buoyancy. Hall 4 suggested that a higher body fat percentage and a lighter portion raised above water increases the efficiency of the upward supporting force. However, although increased body fat increases buoyancy, it also increases form drag (Hamilton 5), which is disadvantageous for moving in water.

In positions with a large airborne weight, for example the highest positions for the upright position, inverted position, and horizontal position, a significant relationship between airborne weight and individual surplus buoyancy was not found. In other words, if the airborne weight increases, there is no effect from the individual difference of the surplus buoyancy. Thus, it is important to increase the propulsion force exerted through propulsive techniques to hold a position with a large airborne weight above water.

V. CONCLUSION

The purpose of this study was to measure airborne weight during basic positions of synchronized swimming to examine the relationship between buoyancy and airborne weight for synchronized swimmers. This study provided the following conclusions;
1) The surplus buoyancy of synchronized swimmers was 2.19 ± 1.78 kgf.
2) In the upright position, the airborne weight of double arm changed from 8.58 ± 0.63 kgf (16.3%) at the shoulders to 28.44 ± 2.99 kgf (53.9%) at the mid-pelvis.
3) In the inverted position, the airborne weight of double leg changes from 3.77 ± 0.97 kgf (7.1%) at the kneecap to 7.77 ± 0.95 kgf (14.7%) at the clotch level.
4) In the horizontal position, the airborne weight for the ballet leg double changed from 7.18 ± 0.94 kgf (13.6%) at the mid-thigh to 12.95 ± 1.72 kgf (24.6%) at the crotch level.
5) Significant correlations were found between individual surplus buoyancy and each position with a small airborne weight.
6) At sites with large volumes such as the torso and thighs, slight differences in the water level result in a large effect on the size of the airborne weight.

Implication for practice
From the results of this study, it suggests that the magnitude and duration of the held airborne weight should be reflected in
the scores given by the Difficulty panel. In addition, it is suggesting that actions involving holding the torso or both legs high above water involve greater difficulty.

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