Optimizing simulation for lower limb motion during throwing in water polo

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Abstract
The objective of this study was to clarify the optimized lower limb motion during throwing in water polo by the simulation. The flexion/extension angles of the hip joint around the ball release were optimized in order to maximize the ball velocity, which corresponded to the hand velocity at the ball release, under the constraint in terms of the hip joint torque and power. The following findings were obtained from the results of optimization: The ball velocity in the case of original joint torque and power limit was 20.8 m/s. The increase in velocity from that of the original motion was 7%. In the case of doubled joint torque and power limits, the increase reached 15%. The characteristic motion in the optimized cases was the kicking forward (flexing) of both lower limbs just before the ball release. The preceding extending motion that was needed to increase the flexing velocity was also found. The increase in the ball velocity in the optimized motions can be explained as the sum of two components. One is the velocity relative to the center of mass of the whole rigid body, and the other is the absolute movement of the rigid body itself. With respect to the relative velocity, the flexing rotation of the lower half of the body produces the counter-rotation of the upper half of the body because of the conservation law of angular momentum. This effect contributed 70% of the total increase in the ball velocity. With respect to the absolute velocity, the rotations around the longitudinal and lateral axes of the inertia were induced by the reaction of kicking the fluid forward. This effect contributed the remaining 30% of the total increase in the ball velocity.

Keywords: Swimming, Sports Biomechanics, Sport Engineering, Muscle and Skelton, Biofluid Dynamics, Optimization, Simulation, Water Polo

1. Introduction

Water polo is a ball game in which two teams consisting of seven players compete for points by shooting a ball into the goal in a swimming pool. In particular, shooting by throwing the ball is an important element since the success rate of the shot strongly affects victory or defeat of the game. Compared to throwing motion in ball games on land (such as handball), throwing in water polo is difficult to perform since the lower half of the player’s body is in the water. Indeed, the player has to throw the ball without any firm base. Therefore, the throwing motion in water polo has been studied by many researchers from the biomechanical viewpoint (Davis and Blanksby, 1977, Whiting et al., 1985, Elliot and Armour, 1988, Feltner and Nelson, 1996, Darras, 1999, Vila et al., 2009, Stevens et al., 2010, McCluskey et al., 2010, Alcaraz et al., 2011, Toyoshima et al., 1974). In these studies, the initial ball velocity (just after releasing the ball) and/or the thrower’s motion were discussed based on the experimental results measured by a motion analysis system, or a speed gun. To summarize these studies, the ball velocity was reported as about 20m/s for male players and 15m/s for female players. Since increasing the ball velocity is important to increasing the success rate of the shot, various factors to increase the ball velocity were discussed in those previous studies. In particular, the motion of the lower half of the body is important. Toyoshima et al. (1974) conducted an experiment in which a player threw a ball with/without the
limitation of the fixed lower half of the body. As a result, a 36.5% reduction in the ball velocity was found when the limitation was present. Therefore, it is necessary to take the motion of the lower half of the body into consideration for the analysis of the throwing motion in water polo. In order to analyze the motion of the lower half of the body, the fluid dynamical aspect is indispensable since the lower half of the body is in the water and is therefore subjected to fluid forces. From this aspect, the simulation model for the throwing motion in water polo was developed by Nakashima et al. (2014). In this model, all the fluid forces acting on the thrower’s body are considered. The absolute movement of the thrower’s body as well as the ball velocity can be calculated by this model. The validity of this model was confirmed in the previous study, since the simulated body movement and ball velocity were sufficiently consistent with the measured ones.

The objective of this study was to clarify the optimized lower limb motion during throwing by using the simulation model of Nakashima et al. (2014). In particular, this study focused on the last phase in the whole throwing motion. The throwing motion in water polo can be generally divided into two phases. In the first phase, the thrower tries to lift his/her body as high as possible. For this purpose, the eggbeater kick or breaststroke kick by the lower limbs as well as the sculling by the free hand (the hand without the ball) are performed. In the last phase, on the other hand, the thrower merely swings back their arm and throws the ball. The desirable lower limb motion during the last phase has not been clarified yet. Indeed, there is no literature referring to the desirable lower limb motion during the last phase. Therefore, the lower limb motion during the last phase is optimized in this study. The simulation model is described in Section 2. The optimizing method is explained in Section 3. The results are shown and discussed in Section 4. The conclusions are summarized in Section 5.

2. Simulation Model

2.1 Swimming human simulation model SWUM

The simulation model in the present study was developed using the swimming human simulation model SWUM, which was developed for analyses of human swimming (Nakashima et al., 2007). The simulation model SWUM was designed to solve the six degrees-of-freedom absolute movement of the whole swimmer’s body as a single rigid body by time integration using the input data of the swimmer’s body geometry and relative joint motion. Therefore, the swimming speed, roll, pitch and yaw motions, propulsive efficiency, joint torques, etc. are computed as the output data. The swimmer’s body is represented by a series of 21 rigid body segments as follows: lower and upper waist, lower and upper chest, shoulder, neck, head, upper and lower hip, thighs, shanks, feet, upper arms, forearms, and hands. Each body segment is represented by a truncated elliptic cone. The unsteady fluid force and gravitational force are taken into account as external forces acting on the whole body. The unsteady fluid force is assumed to be the sum of the inertial force from the added mass of the fluid, normal and tangential drag forces and buoyancy. These components are assumed to be computable, without solving the flow, from the local position, velocity, acceleration, direction, angular velocity, and angular acceleration for each part of the human body at each time step. The coefficients in this fluid force model were identified using the results of an experiment with a limb model and measurements of the drag acting on swimmers in the glide position (Nakashima et al., 2007). To date, SWUM has already been applied to various problems (Nakashima, 2007, Nakashima, 2009, Kiuchi et al., 2010, Nakashima et al., 2010a, Nakashima et al., 2010b, Nakashima, 2010, Nakashima et al., 2012, Nakashima et al., 2013, Nakashima and Ono, 2014). Its details are described in the references, respectively. Some of the analysis data and animation movies are open to the public at the SWUM website (http://www.swum.org/).

2.2 Simulation model for optimizing calculation

The original detailed simulation model for the throwing motion in water polo, which is shown in Fig. 1(a), was developed in the previous study (Nakashima et al. 2014). In this detailed model, the thrower and the ball were modeled as two separate rigid bodies, and connected by virtual springs and dampers. However, the amount of calculation necessary in this model became too large for the optimizing calculation, since the number of time steps had to be high in order to stabilize the relative motion of both the thrower and the ball. Therefore, a simplified model suitable for the optimizing calculation was developed for the present study. In this simplified model, the ball and the right hand of the thrower were modeled as a single body segment, as shown in Fig. 1(b). The geometry of this body segment was changed so that its outer shape, volume and position of center of mass corresponded with those of total values for the
right hand of the thrower and the ball. In order to examine the effect of this simplification, a simulation was conducted. In this simulation, the joint angles of throwing motion for a collegiate water polo player, which was taken by means of a motion capture system in the previous study, was put into the models. The resultant motions in the absolute space were computed. The simulated results for the velocity of the right wrist are shown in Fig. 2. The results of the detailed and simplified models are depicted in the blue and green lines, respectively. The time of ball release was 1.51 s in these simulations. It was found that the velocity of the simplified model (green) was sufficiently consistent with that of the original detailed model (blue) until the ball release. Therefore, it was confirmed that the simplified model could be used for the optimizing calculation. With this simplification, the computing time became 2.5% (40 times faster).

3. Optimizing Method

3.1 Overview

The PSO (Particle Swarm Optimization) (Kennedy and Eberhart, 1995) was used as the optimization algorithm in this study. The flow of the optimizing calculations is as follows: (i) Create 4000 throwing motions randomly and compute objective function for these motions. (ii) Select the best 20 throwing motions as the initial candidates. (iii) Compute objective function for 20 throwing motions. (iv) Based on the PSO algorithm, create new 20 throwing motions. (v) Repeat (iii) and (iv) 100 times. (vi) Obtain the solution as the final best throwing motion.

Since the ball and the thrower’s hand were united in the simplified model as described in the previous section, the ball velocity could not be calculated directly. Therefore, the horizontal velocity of the right hand at the time of ball release, instead of the ball velocity, was used for evaluation. The time of ball release was obtained as the time when the component of the right hand’s acceleration in the palm direction (perpendicular to the palm plane and from the back of the palm to the palm) changed from positive to negative after the cocking motion.

3.2 Objective function
The objective function of the optimization was defined as

\[ G = V_{xy} - P \]  

where \( G \) is the objective function, \( V_{xy} \) is the horizontal component (\( x \)-\( y \) plane component) of the resultant velocity of the right hand at the time of ball release, and \( P \) is the penalty term. This function was maximized in the optimizing calculation. The penalty term \( P \) was added to consider the constraints of the motion in terms of torque and power of the hip joint, which are described later. In the actual calculation, a coefficient was multiplied to the penalty term in order to adjust its magnitude. The value of the coefficient was determined through a trial and error process. In addition, since the first and second terms of the right hand side of Eq. (1) had different units, the coefficient had not clear physical meaning. Therefore, more systematic method to introduce the coefficient in the penalty term will be desired in a future study.

3.3 Design variables

The design variables of the optimization were the hip joint angles, which were the inputs of the simulation model. In the simulation model, the throwing motion was represented as time variation curves of the joint angles. One time variation curve was represented by 20 frames, which were interpolated by the Spline function. The total time of the whole throwing motion was determined to be 1.6 s. As the joint motion at the last phase in the whole throwing motion, the flexion/extension angles of the hip joint at the four frames \( (t = 1.33, 1.42, 1.50 \text{ and } 1.58) \) around the time of ball release \( (t = 1.51 \text{ s}) \) were used for the design variables. The number of design variables was 8 (the 4 frames for the 2 hip joints). The positions of the four frames are shown in Fig. 3(a). The maximum flexion and extension angles were determined as 125 and 30 degrees, respectively, based on the database open to the public (http://www.tech.nite.go.jp/human/). With respect to the joint angles for the other joints as well as the other degrees-of-freedom at the hip joint, those of an actual water polo player, which were measured in the previous study as shown in Fig. 3(b), were put into the simulation model.

Fig. 3  Positions of four time frames as design parameters and original throwing motion.
3.4 Constraint conditions

In order to obtain the reasonable optimized solution which was feasible for a human, the constraint conditions with respect to the torque and power of the hip joints were introduced. For the hip joint torque, the maximum value in the measured results for 140 Japanese males (age: 20 to 49 years old) in the Human Characteristics Database (http://www.tech.nite.go.jp/human/) was used. As a result, 229.5 Nm for the flexion torque and 354 Nm for the extension torque were used, respectively. For the joint power, the experimental study done by Okazaki (2008) was utilized. In their experiment, the averaged values of hip joint power among top nine subjects (totally 18 subjects) were 1236 W for the flexion and 1187 W for the extension, respectively. These values were used. However, joint torque and power generally vary widely according to the angular velocity of the joint. Therefore, the relationship between the joint torque, angular velocity and power was assumed to be as shown in Fig. 4, based on the experimental results of those measured by Kawahatsu and Ikai (1972). In this assumed relationship, the angular velocity was the linear expression of the joint torque, and therefore the joint power became the quadratic expression of the joint torque. The parameters of these functions were determined so that the maximum values of the torque and power in the curves were consistent with those of the experimental values in the abovementioned previous studies. In the optimizing simulation, the maximum voluntary power corresponding to the angular velocity of the hip joint at the moment was obtained from the curves of Fig. 4. If the joint power calculated in the simulation exceeded those maximum values, the exceeded amounts were subtracted from the objective function as the penalty term which is denoted by $P$ in Eq. (1).

Since those maximum voluntary values were measured in the condition that the muscle contracted continuously for a certain period, there is a possibility that the thrower can instantaneously produce joint power that surpasses the aforesaid maximum values. Therefore, in addition to the abovementioned constraint condition, the optimizing simulations were also conducted for the cases where all the maximum values of joint torque and power were increased by half (1.5 times) as well as doubled (2.0 times). These three conditions are denoted by “limit 1.0 times”, “limit 1.5 times” and “limit 2.0 times” in the following, respectively.

4. Results and Discussion

4.1 Obtained optimized motions

First, it was examined whether the resultant hip joint power was successfully constrained by the penalty term in the objective function. The torque-power relationships of the hip joint for the optimized motions are shown in Fig. 5. The right and left sides are the flexion and extension, respectively. The values of the torque and power of the hip joint during $t = 1.25 \sim 1.51$ s are plotted in the graphs. The black and white circles represent the right and left hip joints, respectively. The solid lines represent the maximum joint power as the constraint condition. From these graphs, it was confirmed that the joint powers of the optimized motions were successfully constrained since all the black and white circles were on or below the solid lines. It was also found that the hip joint power in the two cases of limit 1.5 and 2.0 times reached the limit only for the flexion.

The resultant ball velocities (hand velocities at the ball release) obtained by the simulation are shown in Fig. 6. Compared to the original velocity of 19.5 m/s, the velocity increased to 20.8 m/s (7% faster) even in the case of limit
1.0 times. This velocity increase generally corresponds to the difference between collegiate and national players in Japan. In addition, the velocity increase reached 15 % in the case of limit 2.0 times.

The throwing motions obtained in the optimizing simulations are shown in Fig. 7. In these images, the directions

Fig. 5  Torque-power relationships of the hip joint for the optimized motions.

Fig. 6  Resultant ball velocities (hand velocities at the ball release).
and magnitudes of the fluid forces acting on the thrower’s body are represented by red lines, and the water surfaces are represented by the checkered pattern in the pale blue. In the figure, the thrower’s motions did not seem apparently different from the original motion shown in Fig. 3(b). However, it was found that the red lines from both feet became longer (the fluid forces acting on the feet became larger) at $t = 1.51$ s for the optimized motions, especially for the case of limit 2.0 times. This indicates that the thrower kicks forward in the optimized motions. The time histories of the hip joint angles for flexion/extension are shown in Fig. 8. The positive and negative values in the graphs are angles of flexion and extension, respectively. From Fig. 8(a), it was found that the right hip was flexing (varying from negative to positive) at the time of ball release ($t = 1.51$ s) for the optimized motions, while it was almost constant for the original motion. In addition, the slopes of the curves at $t = 1.51$ s became steeper when the limit became larger. This steeper slope was realized by first extending the hip joint before the start of flexing. From Fig. 8(b), it was found that the slopes at $t = 1.51$ s became steeper for the optimized motions with larger limits, by delaying the starting time of the flexion. For example, the angle for the original motion became zero before the flexion at $t = 1.39$ s, while those for the optimized motions of limits 1.5 and 2.0 times became zero at $t = 1.43$ s. Therefore, it can be concluded that the kicking forward by both legs is essential to increase the ball velocity.

The time histories of the hip joint power during concentric contraction (positive power generation) are shown in

![Fig. 7 Throwing motions obtained by optimizing simulation.](image)

![Fig. 8 Time histories of hip joint angles for flexion/extension.](image)
Fig. 9. The positive and negative sides correspond to the flexion and extension, respectively. From the figure, it was found that the right hip joint (blue line) in the original motion did not perform any active work. However, in the optimized motions, it participated in the flexing motion just before the ball release. In addition, the peak value of this flexing motion became larger when the power limit became larger. The extending motion mainly by the right hip joint at $t = 1.35$ s became also more significant when the power limit became larger. This extending motion is considered to be the preparation for the coming flexing motion.

4.2 Discussion about reasons for increase in the ball velocity

The reasons for the increase in the ball velocity for the optimized motions are discussed in this subsection. When the thrower and the ball are regarded as one rigid body, the ball velocity can be expressed as the sum of two components. One is the velocity relative to the center of mass of the whole rigid body, and the other is the absolute velocity of the rigid body itself. Therefore, each component was examined one by one. First, in order to investigate the relative component, virtual simulations without the external forces were conducted. In these simulations, all the external forces, such as the fluid forces and the gravitational force, were not taken into account in the equations of motions. Therefore, the center of mass of one rigid body consisting of the thrower and the ball did not move at all. The resulting ball velocities are shown in Fig. 10. It was found that the ball velocity of limit 1.0 times was larger than that of the original motion. It was also found that the ball velocity increased according to the increase in the joint power limit. The difference between the original motion and limit 2.0 times was 2.0 m/s, which was 70% of the total difference between 19.5 m/s (original) and 22.4 m/s (limit 2.0 times) shown in Fig. 6. Therefore, the main reason of the increase in the ball velocity for the optimized motions was the increase in the hand velocity relative to the center of mass of the thrower and the ball. The mechanism of this reason is schematically shown in Fig. 11. In the optimized motions, the hip joint was flexing just before the ball release (the purple arrow in the figure). This flexing rotation produces the counter-rotation of the upper half of the body (the red arrow in the figure) because of the conservation law of angular momentum. This rotation of the upper half of the body causes the increase in the ball velocity.

Next, the absolute velocities of the rigid body were investigated. With respect to the translational velocity, it was constantly 1.0 m/s for all four cases (original, limit 1.0, 1.5 and 2.0 times). Therefore it was not the reason for the
increase in the ball velocity for the optimized motions. With respect to the rotational velocity, each component about each principal axis of inertia was examined. The three principal axes of inertia of the thrower and the ball as one rigid body at the ball release are shown in Fig. 12(a). The red, blue and green lines are the longitudinal, lateral and sagittal axes, respectively. The directions of these axes were calculated based on the mass distribution. The contributions of the rotational movements to the ball velocity are shown in Fig. 12(b). In order to obtain each contribution, the velocity component at the center of the ball which was induced by each rotational movement was firstly calculated by taking the product of the angular velocity and the distance between the center of mass of the rigid body and the center of the ball. The contribution was next calculated by taking the component of the calculated velocity component in the direction of the ball velocity. From Fig. 12(b), it was found that all the three rotational movements contributed positively to the ball velocity, since all the values were positive. It was also found that the contributions of the rotations about the longitudinal and lateral axes for the optimized motions were larger than that for the original motion, while the contribution about the sagittal axis did not change much for all the four cases. In addition, the sum of the contributions increase in the ball velocity for the optimized motions. With respect to the rotational velocity, each component about each principal axis of inertia was examined. The three principal axes of inertia of the thrower and the ball as one rigid body at the ball release are shown in Fig. 12(a). The red, blue and green lines are the longitudinal, lateral and sagittal axes, respectively. The directions of these axes were calculated based on the mass distribution. The contributions of the rotational movements to the ball velocity are shown in Fig. 12(b). In order to obtain each contribution, the velocity component at the center of the ball which was induced by each rotational movement was firstly calculated by taking the product of the angular velocity and the distance between the center of mass of the rigid body and the center of the ball. The contribution was next calculated by taking the component of the calculated velocity component in the direction of the ball velocity. From Fig. 12(b), it was found that all the three rotational movements contributed positively to the ball velocity, since all the values were positive. It was also found that the contributions of the rotations about the longitudinal and lateral axes for the optimized motions were larger than that for the original motion, while the contribution about the sagittal axis did not change much for all the four cases. In addition, the sum of the contributions...
about the longitudinal and lateral axes became larger when the joint power limit became larger. The resultant contribution of the rotational movement could be calculated by taking the square root of the square sum of the three contributions for the three axes. The difference of this resultant contribution between the original and limit 2.0 times was found to be 0.79 m/s, which was about 30% of the total difference of the ball velocity (2.9 m/s).

The cause for the increase in the contributions about the lateral axes was considered to be the reaction against kicking forward in the optimized motions. The fluid forces for the rotation about the lateral axis are shown in Fig. 13(a). As the reaction against kicking forward, large fluid forces acted on the feet, as marked with blue ellipses. The clockwise rotation (black arrow) was induced as a result. The reason for the increase in the contributions about the longitudinal axis was also considered to be in reaction against kicking forward. The fluid forces for the rotation about the longitudinal axis are shown in Fig. 13(b). It was found that the fluid forces acted on the shank in the right direction (marked with blue ellipses). These fluid forces induced the counterclockwise rotation. The mechanism for the generation of these fluid forces is shown in Fig. 13(c). Indeed, the flexion/extension axis at the hip joint (the orange line) was not perpendicular to the longitudinal axis but inclined as shown in the figure. Therefore, the kicking direction (the black dotted arrows) and the resultant fluid forces (the black solid arrows) were also inclined. As a result, the fluid forces had not only the component for the rotation about the lateral axis (the blue arrows) but also the component for the rotation about the longitudinal axis (the red arrows).

5. Conclusions

In this study, the optimizing simulation was conducted for the lower limb motion during throwing in water polo. In the simulation, the flexion/extension angles of the hip joint around the ball release were optimized in order to maximize the ball velocity, which corresponded to the hand velocity at the ball release, under the constraint in terms of the hip joint torque and power. The findings are summarized as follows:

(1 ) The ball velocity in the case of original joint torque and power limit was 20.8 m/s. The increase in velocity from that of the original motion was 7%. In the case of doubled joint torque and power limits, the increase reached 15%.

(2 ) The characteristic motion in the optimized cases was the kicking forward (flexing) by both lower limbs just before the ball release. The preceding extending motion in order to increase the flexing velocity was also found.

(3 ) The increase in the ball velocity in the optimized motions can be explained as the sum of two components. One is the velocity relative to the center of mass of the whole rigid body, and the other is the absolute movement of the rigid body itself. With respect to the relative velocity, the flexing rotation of the lower half of the body produces the counter-rotation of the upper half of the body because of the conservation law of angular momentum. This effect
contributed 70% of the total increase in the ball velocity. With respect to the absolute velocity, the rotations about the longitudinal and lateral axes of the inertia were induced by the reaction of kicking the fluid forward. This effect contributed the remaining 30% of the total increase in the ball velocity.

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