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Development of an algorithm to estimate soaking posture in the bathwater

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Abstract
Soaking in bathwater has been a familiar custom for the Japanese for a long period of time. The authors discussed bathing comfort from the viewpoint of biomechanics in a previous study. However, it took a lot of effort to evaluate the joint torques during soaking in the water while conducting the experiments. Therefore, it was required to estimate the soaking postures and center of pressure (COP) in order to conduct the biomechanical evaluation with minimal experiments. The objective of this research was to develop an algorithm to estimate soaking posture and COP. In this study, it was assumed that a human took a soaking posture in the bathtub so as to minimize muscle exertion, that is, to minimize the joint torque as much as possible. Based on this assumption, an algorithm to estimate the soaking posture was constructed as an optimization problem of the objective function. An experiment was conducted for the purpose of validating the estimation algorithm. In this experiment, three kinds of bathtub shapes were tested for five healthy males. As a result, the estimated posture and COP were in good agreement with the measured one. The maximum error of the joint angle was 6.0% among all participants. The average values of the error in the location of the COP for each condition were 0.01 m or less. From the results of the present study, the possibility of estimation the joint torque is suggested.

Keywords : Biomechanics, Bathtub, Soaking posture, Center of pressure(COP), Joint torque, Simulation

1. Introduction

Soaking in bathwater has been a familiar custom for the Japanese for a long period of time. Its objectives are not only to warm the body, but also to become relaxed. The authors discussed bathing comfort not from the viewpoint of thermal effects nor physiological effects such as many previous studies investigated (Oyake et al., 1999; Yanagihashi et al., 1996), but from the viewpoint of biomechanics. The joint torques as biomechanical loads were quantitatively evaluated constructing a biomechanical soaking model in the previous study (Nakamura et al., 2018). It was shown that there is a possibility of improving the comfort of soaking by designing the shape of the bathtubs with consideration of such biomechanical loads. Furthermore, Kato et al. (2016) demonstrated a possibility that relieving the physical loads in soaking can induce the feeling of comfort in the brain from the viewpoints of biomechanics and neurophysiology. However, it took a lot of effort to evaluate soaking postures in the water using the experimental method conducted in the previous researches. In addition, the shape of the bathtub has many parameters, such as the angle of reclining, the length of the bathtub and the height of the footrest. Therefore, many conditions are required for the consideration to decide the shape.

In order to solve this problem, Fujii et al. (2017) developed an algorithm to estimate reaction forces that act on a human from a bathtub so that the biomechanical evaluation can be efficiently conducted without experiments in water. In addition, their research suggested a mechanism of human posture control in water validating the algorithm which includes potential human consciousness, for example, to minimize the reaction forces which support human posture. However, the soaking posture itself was not estimated in their study. Their algorithm could be applied only when measured or assumed postures were given. The soaking postures were still required to measure through experiments. Indeed, the soaking postures are also required in order to calculate the joint torque as an evaluation index. Therefore, it was required to estimate the soaking postures in order to conduct the biomechanical evaluation with minimal experiments. Furthermore, the measured center of pressure (hereinafter referred to as COP) of the reaction forces was put into their algorithm, and thus it was also necessary to be estimated.

The objective of this research was to develop an algorithm to estimate the soaking posture and COP. If such algorithm is realized and combined with the previous algorithm to estimate the reaction forces, the comfort of the bathtubs can be evaluated on the simulation without experiments in water in the future, once the bathtub is designed. It would enable a manufacturer to design a bathtub based on quantitative discussions. In addition, such algorithm will contribute to a better understanding of how humans control the soaking postures under specific conditions, such as soaking in water. In this study, the algorithm to estimate the soaking posture and COP was developed and validated.

2. Method

2.1 Biomechanical model of soaking posture in bathtub

In this study, it was assumed that a bather was in contact with a bathtub at the back, the hip and the feet while soaking in the bathtub, and that the bather took a symmetrical posture. Additionally, the model was assumed to be static and only in the sagittal plane. As shown in Fig. 1, the soaking posture was defined as two dimensional coordinates of ten physical feature points (vertex, acromion, axillary fossa, sternum lower end, waist, L4/L5 point, greater trochanter, femur lateral epicondyle, lateral malleolus, metatarsal fibulare). The lateral malleolus, the femur lateral epicondyle, the great trochanter and the L4/L5point were defined as the location of the ankle joint, the knee joint, the hip joint and the lumbar respectively.

During soaking in a bathtub, torques due to gravity, buoyancy, the reaction force and passive elastic joint properties acted on each joint, e.g. the hip joint, the knee joint, the ankle joint and the lumbar. In order to maintain the posture, the joint torques which were calculated as biomechanical loads balance these torques. The torques due to gravity, buoyancy, the reaction force and passive elastic joint properties were calculated by a biomechanical model, whose details were described in the previous study (Nakamura et al., 2018).

2.2 Algorithm to estimate soaking posture

For a certain shape of the bathtub, there are various soaking postures that a human can take. However, a human settles in a specific posture during soaking in water, if he/she is asked to take his/her most comfortable posture. Therefore, it was considered that a human determined their posture according to some posture mechanism. In this study, it was assumed that a human took a soaking posture in the bathtub so as to minimize muscle exertion, that is, to minimize the joint torque as much as possible. Based on this assumption, an algorithm to estimate the soaking posture was constructed as an optimization problem of the objective function shown in Eq. (1).

$$f = k_0 {\tau_a}^2 + k_1 {\tau_k}^2 + k_2 {\tau_h}^2 + k_3 {\tau_l}^2 + k_4 {\tau_{pas-m}}^2 \tag{1}$$

Here, τ_a, τ_k, τ_h, τ_l are the joint torques at the ankle joint, the knee joint, the hip joint and the lumbar, respectively, and τ_{pas-m} is the passive elastic joint torque at the metatarsal fibulare.

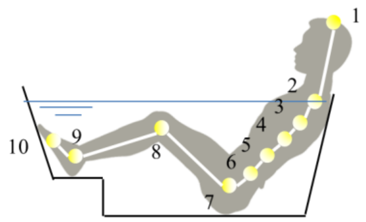

Fig. 1 Definition of soaking posture. Soaking posture was represented by 10 feature points (vertex, acromion, axillary fossa, sternum lower end, waist, L4/L5 point, greater trochanter, femur lateral epicondyle, lateral malleolus, metatarsal fibulare) on the body. Joint angle at the ankle, the knee, the hip and the lumbar were calculated from coordinate data.

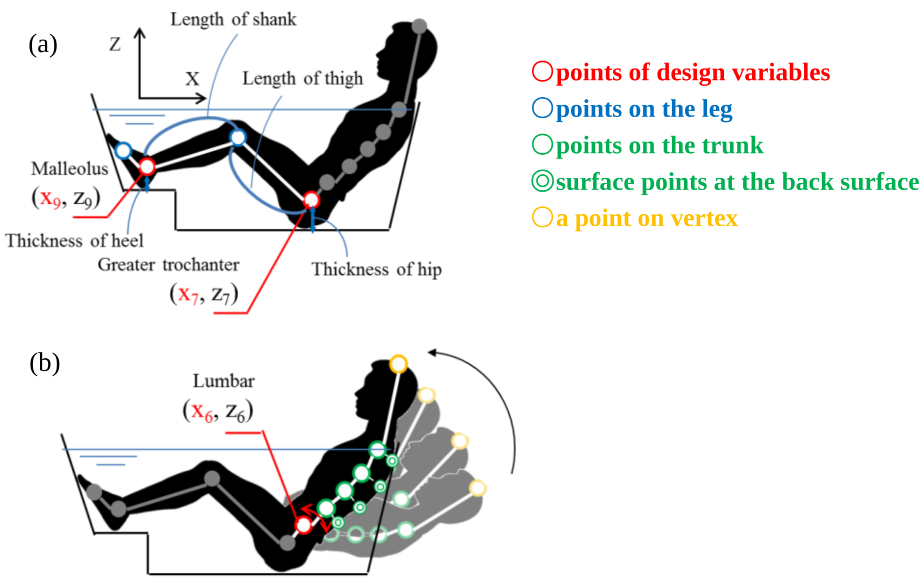

Fig. 2 Schematic view of an algorithm to calculate soaking posture. Horizontal coordinates at the hip joint, the ankle joint and the lumbar were determined as design variables. (a) Leg posture was determined on the basis of constrained condition; (b) Trunk posture was determined to locate back inside the bathtub.

For the design variables of the optimization problem, the horizontal coordinates of the lumbar (x_6 in Fig. 2), the greater trochanter (x_7) and the ankle joint (x_9) were used. The other coordinates were calculated as dependent variables, based on the geometrical relationships and the constraint conditions obtained from the experimental results, considering lengths of body segments and body thickness for each bather. The constraint conditions are as follows:

(i) The sole contacts with the wall at the foot side, and the heel contacts with the bottom at the foot side. However, the entire sole does not necessarily fit with the wall surface.
(ii) The trunk is located inside the dorsal wall.
(iii) The hip is on the bottom of the bathtub.

The coordinates for the legs (x_8, x_{10}, z_7~z_{10}) could be obtained from the geometrical relationships and the constraint conditions (i) and (iii), as well as the body length and the body thickness for each bather, once the coordinates x_7 and x_9 were given. This relationship is schematically shown in Fig. 2(a). As shown in the figure, z_7 and z_9 can be calculated if the body thickness at the hip and heel are known, respectively. Once z_7 and z_9 are determined, the locations of two red points are determined. Thus x_8 and z_8 (the location of knee) can be obtained if the lengths of the thigh and shank are known. The algorithm to determine the coordinates for the trunk (x_1~x_6, z_1~z_6) is schematically shown in Fig. 2(b). From preliminary experiments, it was found that the trunk posture (the relative angles between the adjacent segments) almost did not change at all even if the bathtub shape was changed. Therefore, it was assumed that the trunk posture was fixed, that is, the geometrical relationships among the single green circles in Fig. 2(b) were fixed. On this assumption, the trunk could be rotated about (x_6, z_6) as a whole, and the angle of the trunk was determined from the constraint condition (ii). For this purpose, additional surface points at the body's back (the double green circles in Fig. 2(b)) were introduced based on the measured results of body thickness of the trunk. As shown in Fig. 2(b), the trunk first took the horizontal position, and was rotated in the counter-clockwise direction until all the surface points were located inside the dorsal wall. The coordinates for the head (x_1, z_1) were determined so as to minimize the joint torque at the neck. The posture was completely determined from the above procedure. Then the joint torques and the objective function were calculated. Here, the measured reaction forces were entered into the calculation of the joint torques. The design variables (x_6, x_7 and x_9) were changed based on the optimization algorithm, and the above procedure was repeated until the objective function became minimum. The downhill simplex method was employed for the optimization alogrithm.

2.3 Algorithm to estimate COP of reaction forces

When the soaking posture changes, the COP at each contact point is generally displaced with the changes of the contact condition between the bather and the bathtub. This also affects the torque due to the reaction force and the joint torque. Therefore, an algorithm to estimate the displacement of the COP was constructed. Basically, the bather was supported by three points on the back, the hip and the foot. The locations of these three points were estimated. Regarding the COP on the back, surface points on the back were calculated from the measurement points in the same way as the estimation of the trunk angle. Furthermore, in order to obtain the contact point precisely, the five surface points were interpolated using the spline interpolation, as shown in Fig. 3. Thus, the dorsal surface was approximated by more continuous curve with increased surface points to 100 points. Then, the distances between the surface points and the wall of the bathtub were calculated (the double headed gray arrows in Fig. 3). Further, intersections of vertical lines drawn from each surface point to the bathtub and the wall of the bathtub were calculated. Finally, as shown in Eqs. (2) and (3), COP on the back was estimated by weighting the coordinates of the intersections according to the reciprocals of the distances. Here, d_i are the distances between the surface points and the bathtub, x_i and z_i are the horizontal and vertical coordinates of the intersections.

The horizontal coordinate of COP on the hip was estimated from Eq. (4). Here, x_7 is the horizontal coordinate of the hip joint, COG_x is the horizontal coordinate of the center of gravity of the bather (hereinafter referred to as COG) and m_1 and m_2 are coefficients for each subject. Basically, the horizontal coordinate of COP on the hip was considered to be close to the horizontal coordinate of the hip joint. Moreover, it was assumed that the horizontal component of the difference between the hip joint and COG could induce slight displacement of COP, and this influence was considered by adding a linear function.

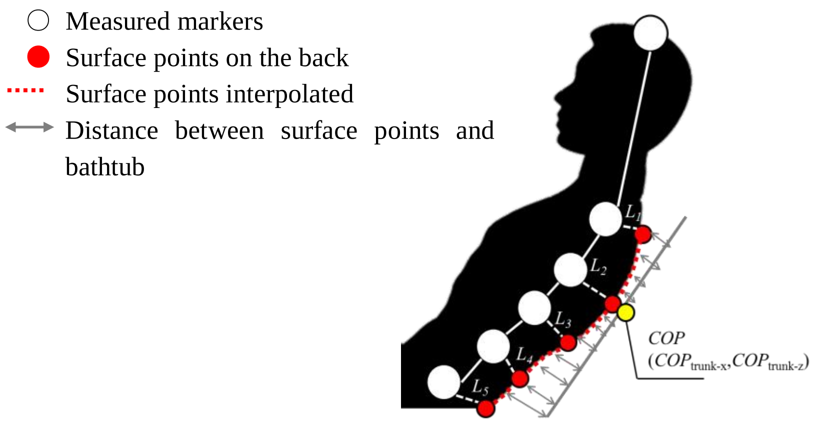

Fig. 3 Schematic view of an algorithm to estimate COP on back. COP was estimated from distance between surface points on the back, which were interpolated using spline interpolation, and bathtub.

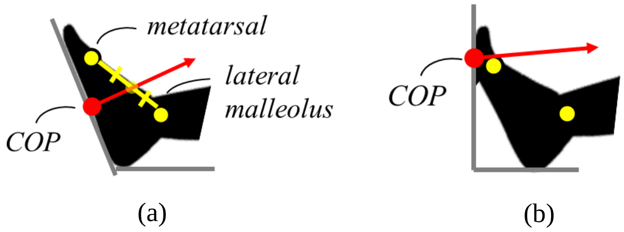

Fig. 4 Schematic view of an algorithm to estimate COP on foot. (a) In the case in which wall of bathtub is fitted with the entire sole, line of action force from COP was assumed to pass through the midpoint; (b) In the case in which wall of bathtub is not fitted with the entire sole, COP was assumed to locate on the thenar area.

The coefficients m_1 and m_2 in the function were determined so that the difference between the estimated value and the measured value of COP became small for each subject.

The COP of the foot was calculated in two ways according to the pattern of contacting with the bathtub wall, as shown in Fig. 4. It was observed in the experiment that there were two ways to contact with the bathtub wall, that is, when the entire sole fitted with the bathtub wall and when only the toe and the heel contacted with the wall. When the entire sole fitted with the wall, first the midpoint of the lateral malleolus and the metatarsal was calculated, as shown in Fig. 4(a). Then, it was assumed that the COP could be calculated as the point from which the reaction force vector started and passed through the midpoint. When only the toe and the heel contacted with the wall, it was assumed that the COP was located in the thenar area as shown in Fig. 4(b). Here, the location of COP was determined by the positional relationship with metatarsal fibulare for each participant from preliminary experiment. It was observed in the experiment that the reaction force in the vertical direction on the foot was small and mainly the reaction force in the horizontal direction acted on the foot, even if the heel was contacted with the bottom. It was considered that force in the horizontal direction on the heel was due to friction and thus negligibly small.

$$COP_{trunk-x} = \left(\sum_i 1/d_i \times x_i\right) / \left(\sum_i 1/d_i\right) \tag{2}$$

$$COP_{trunk-z} = \left(\sum_i 1/d_i \times z_i\right) / \left(\sum_i 1/d_i\right) \tag{3}$$

$$COP_{hip-x} = x_7 + m_1\{COG_x - x_7\} + m_2 \tag{4}$$

2.4 Measurement

An experiment was conducted for the purpose of validating the posture estimation algorithm. In this experiment, the three kinds of bathtub shapes (con1, con2, con3) shown in Fig. 5 were tested by five healthy males (mean ± SD; height 170.0±5.6 cm, body weight 65.4±8.8 kg, Min ~ Max; height 166 ~ 180 cm, body weight 56 ~ 76 kg). The

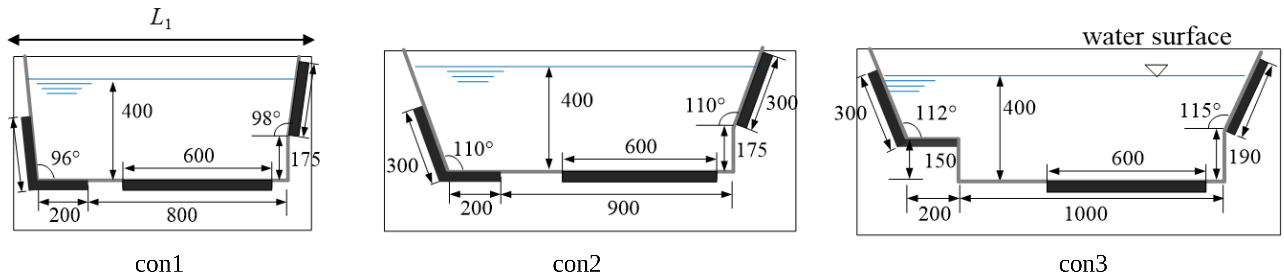

Fig. 5 Bathtub conditions. Three types of bathtub were used to evaluate soaking postures. Black rectangles represent force plates.

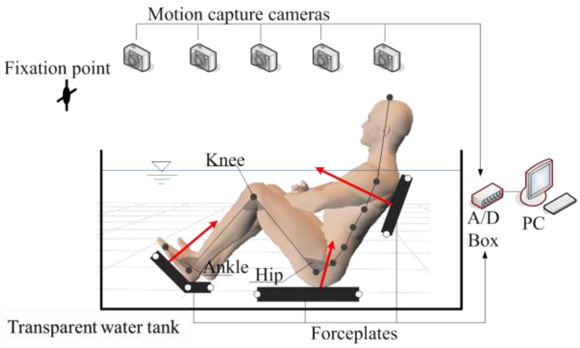

Fig. 6 Schematic view of experimental setup. Soaking posture and reaction forces from the bathtub were measured using a three-dimensional motion analysis system and three-dimensional force plates in the water tank.

bathtub conditions were selected from bathtubs whose longitudinal length L_1 is from 1200 mm to 1600 mm, which is the popular size in Japan. The longitudinal length L_1 were 1200 mm, 1600 mm and 1600 mm in con1, con2 and com3, respectively. The lengths of bathtub bottom were 1000 mm, 1100 mm and 1200 mm in con1, con2 and con3, respectively. Participants were only instructed to take the most comfortable posture and to cross their arms in front of the trunk. The soaking postures and the reaction forces from the bathtub were measured.The water level height was adjusted so that it always became 400 mm during soaking by adding or removing water. The location of force plates were adjusted so that the bathtub shape condition was reproduced in the transparent water tank, as shown in Fig. 6. Force plates (TF-3040-W and TF-2030-W, Tech Gihan, Japan) were installed at the back, hip and feet, to measure the reaction forces on each point of action. Regarding the soaking posture, a three-dimensional motion analysis system (VENUS 3 D R, Nobby Tech, Japan) was used to measure the position coordinates of ten self luminous markers put on the left side of the participants' bodies (the black circles in Fig. 6). The position coordinates of seven luminous markers on the force plates were measured as well (the white circles in Fig. 6). Data were obtained for 30 s at 30 Hz and low-pass filtered at 10 Hz using a fourth-order Butterworth filter.

In this study, all participants gave their written informed consent. The study was approved by the TOTO Ltd. ethics board.

2.5 Procedure for analysis

The initial values of x_6, x_7 and x_9, the bathtub shape, the lengths of body segments, the width and thickness for each participant and k_0~ k_4 in the objective function were put into calculation for estimation of the soaking posture. The initial values of x_6, x_7 and x_9 were determined taking into account that i) the sole contacts with the foot side wall surface ii) the length between the ankle joint and the hip joint is smaller than the sum of the shank length and thigh length. From the initial values of x_6, x_7 and x_9, the soaking posture was geometrically determined as described above, and the COP at the soaking posture was estimated. Then, the joint torques and the objective function were calculated from the estimated posture and COP with the measured reaction forces. The estimated soaking posture was determined after repeating the above process until the objective function was minimized. The weights in the objective function were determined by the parameter study so that the sum of differences between the measured value of the joint torque and the estimated value for con1 and con3 was minimized. Table 1 shows the resultant weights of the objective function. The variation among participants was considered to be due to differences in preference and physical constitution for each participant. The soaking posture in con2 was completely estimated by using these coefficients.

Table 1 Coefficients of objective function.

	Participant1	Participant2	Participant3	Participant4	Participant5
k_0	5	20	264	50	0.06
k_1	10	10	29	151	0.07
k_2	3	3	0.5	6	0.05
k_3	1	1.5	1	1	1
k_4	12	30	42	362	100

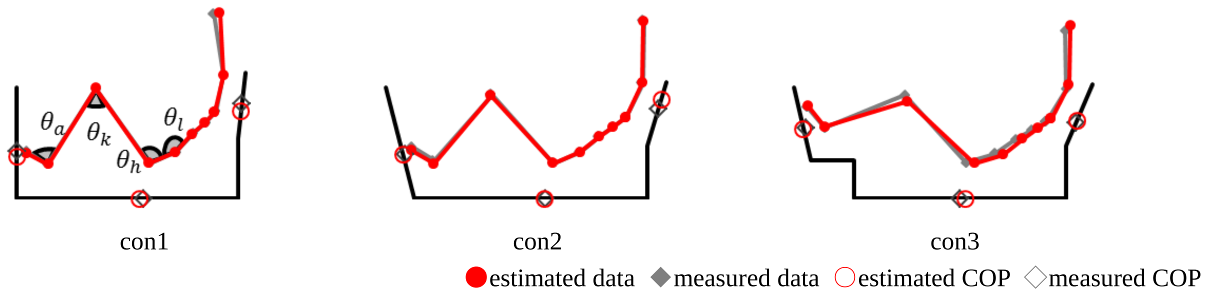

Fig. 7 Estimation of soaking posture and COP (Participant3). Red and gray circles represent estimated and measured data, respectively. Marks on the bathtub surface represent the location of COP.

3. Results

3.1 Joint angles

Fig. 7 shows typical estimated results of soaking posture and COP for one participant. The estimated posture was in good agreement with the measured one, especially for con2, which was the completely estimated case. In order to evaluate the estimated soaking posture more quantitatively, the joint angles at the ankle, knee, hip and lumbar $\theta_a, \theta_k, \theta_h$ and θ_l were calculated as defined in Fig. 7, and the estimated values and measured values were compared. Fig. 8 shows the estimated and measured values of each joint averaged for all the participants. Error bars indicate standard errors. At the ankle joint, knee joint and hip joint, the measured value of the joint angles increased to extension/plantar flexion in order of con1, con2 and con3. This was due to an increase in the length of bathtub bottom, and the same change was obtained in the estimated value. At the lumbar, the measured joint angle increased from con1 to con2, while there was no difference between con2 and con3. Therefore, the position of the trunk did not change significantly, but the change of the leg posture could absorb the narrowness of the bathtub, when the length of the bathtub bottom is larger than a certain value. However, when the length of bathtub bottom became less than a certain value, a change in trunk posture may be necessary for absorption of the narrowness in addition to the change in leg posture. This phenomenon was reproduced even with the estimated results. Moreover, in order to evaluate estimation accuracy, the error between the measured and estimated values was defined by Eq. (5). Here, θ_{est} is an estimated value of each joint angle, and θ_{exp} is an actually measured value of each joint angle.

$$E_{ang} = \frac{1}{4} \times \sum^{4} \left| \frac{\theta_{est} - \theta_{exp}}{\theta_{exp}} \right| \times 100 \tag{5}$$

Table 2 shows errors for each participant and each condition. The participants average of errors from con1 to con3 were 2.9 %, 3.4 % and 2.8 %, and up to 6.0 % throughout all participants.

3.2 COP

As shown in Fig. 7, the estimated values for the COP were in good agreement with the measured values. In order to quantitatively evaluate the estimated COP, we compared the difference between the measured and estimated values in the horizontal and vertical directions. Table 3 shows the results. The values in the first to third rows were the difference between the participant average values, the values in the fourth row were the average values for all conditions, and the values in the fifth row are the maximum values of the magnitude of the difference in each subject. Regarding the mean values in the horizontal and vertical directions, the differences were on the order of several millimeters, except for 0.016 m of the horizontal direction at the hip. The maximum values of the vertical components at the back and the horizontal components at the hip were 0.064 m and 0.054 m, but the other components were about half of their value.

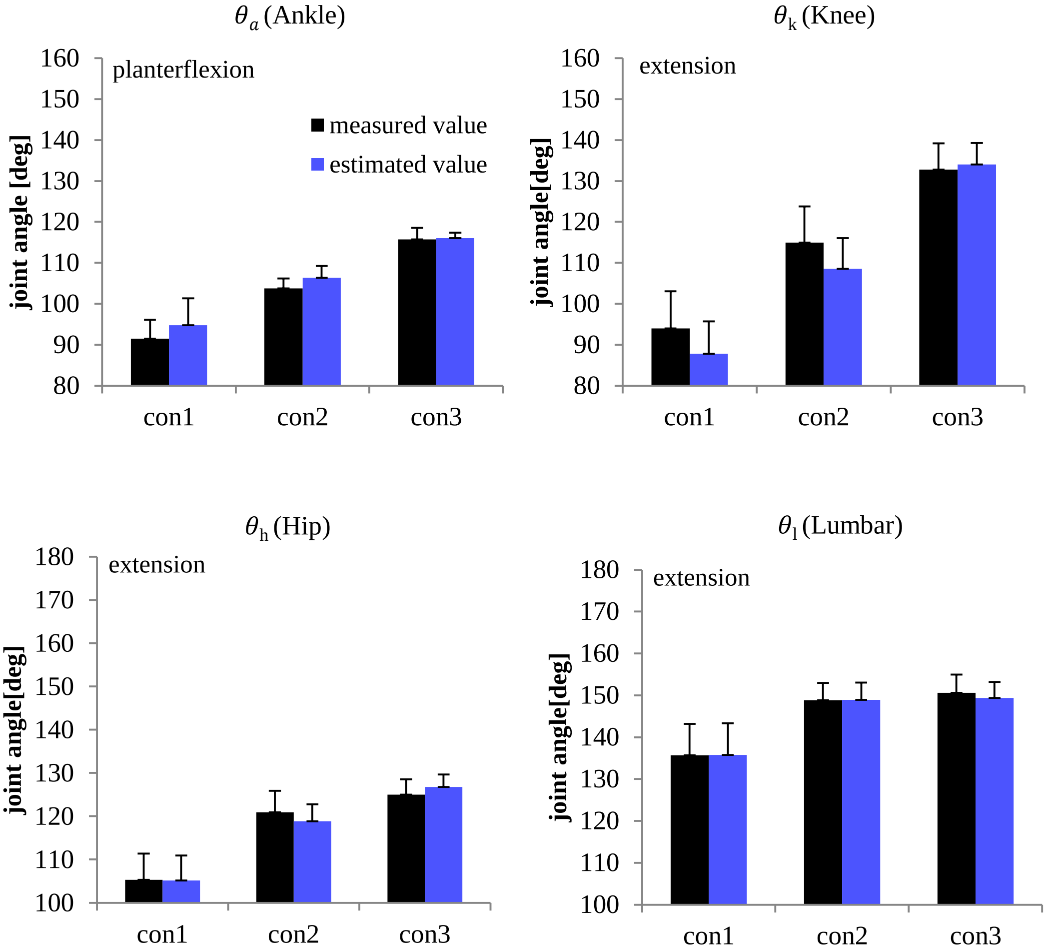

Fig. 8 Estimated joint angles and measured joint angles at each joints. Measured joint angles at the ankle, knee and hip were increased in order of condition number. Measured joint angle at the lumbar in con1 was smaller than angles in con2 and con3. Estimated values were consistent with measured values.

Table 2 Error of joint angles in percentage.

	Participant 1	Participant 2	Participant 3	Participant 4	Participant5	Average
con1	4.8	1.7	2.3	3.6	2.2	2.9
con2	4.3	2.6	1.9	6.0	2.4	3.4
con3	3.1	0.5	5.5	1.2	3.7	2.8

Table 3 Distance of estimated COP and measured COP.

[m]	Trunk x	Trunk z	Hip x	Hip z	Foot x	Foot z
con1	-0.002	-0.012	-0.017	0	0.000	-0.015
con2	-0.001	-0.004	-0.010	0	-0.015	0.004
con3	0.004	0.010	0.020	0	-0.004	-0.013
Ave	0.003	0.009	0.016	0	0.006	0.010
Max	0.024	0.064	0.054	0	0.028	0.033

3.3 Joint torque

Fig. 9 shows the measured values and estimated values of the joint torques at the ankle, the knee, the hip and the lumbar (τ_a, τ_k, τ_h and τ_l). The measured values of the joint torques at the ankle and hip joints decreased in order of con1, con2 and con3 (con1: $\tau_a = 6.9$ Nm, $\tau_h = 13.7$ Nm, con2: $\tau_a = 2.5$ Nm , $\tau_h = 7.5$ Nm, con3: $\tau_a = 1.0$ Nm, $\tau_h = 4.7$ Nm). This suggested that the biomechanical load on the body was reduced. The estimated values of the joint torques were in good agreement with the measured values (con1: $\tau_a = 5.9$ Nm, $\tau_h = 12.9$ Nm, con2: $\tau_a = 0.7$ Nm, $\tau_h = 6.6$ Nm, con3: $\tau_a = 0.9$ Nm, $\tau_h = 3.1$ Nm). The joint torque at the knee joint was reduced in order of con2, con1 and con3 (con1: $\tau_k = 3.4$ Nm, con2: $\tau_k = 5.6$ Nm, con3: $\tau_k = 2.4$ N), and the estimated value was changed similarly (con1: $\tau_k = 3.2$ Nm, con2: $\tau_k = 4.2$ Nm, con3: $\tau_k = 2.4$ Nm). The measured joint torque at the lumbar in con1 was larger than the joint torque in con2 and con3 (con1: $\tau_l = 87.0$ Nm, con2: $\tau_l = 20.6$ Nm, con3: $\tau_l = 19.7$ Nm), and the estimated value was changed similarly (con1: $\tau_l = 88.2$ Nm, con2: $\tau_l = 20.7$ Nm, con3: $\tau_l = 21.7$ Nm).

The error was defined by Eq. (6) to quantitatively evaluate the accuracy, and the calculated results were shown in Table 4. Here, τ_{est} is the estimated joint torque at each joint, τ_{exp} is the measured value, and H and W are the height and the weight of each subject. It was suggested that a high accuracy estimation was achieved since the error was up to 0.26 %.

$$E_{trq} = \frac{1}{4} \times \sum^{4} \left| \frac{\tau_{est} - \tau_{exp}}{H \times W} \right| \times 100 \tag{6}$$

4. Discussion

The validity of the estimation algorithm in this study was verified by comparing the measured values of the soaking posture, COP and the joint torques with the estimated values. The maximum error of the joint angle was 6.0%

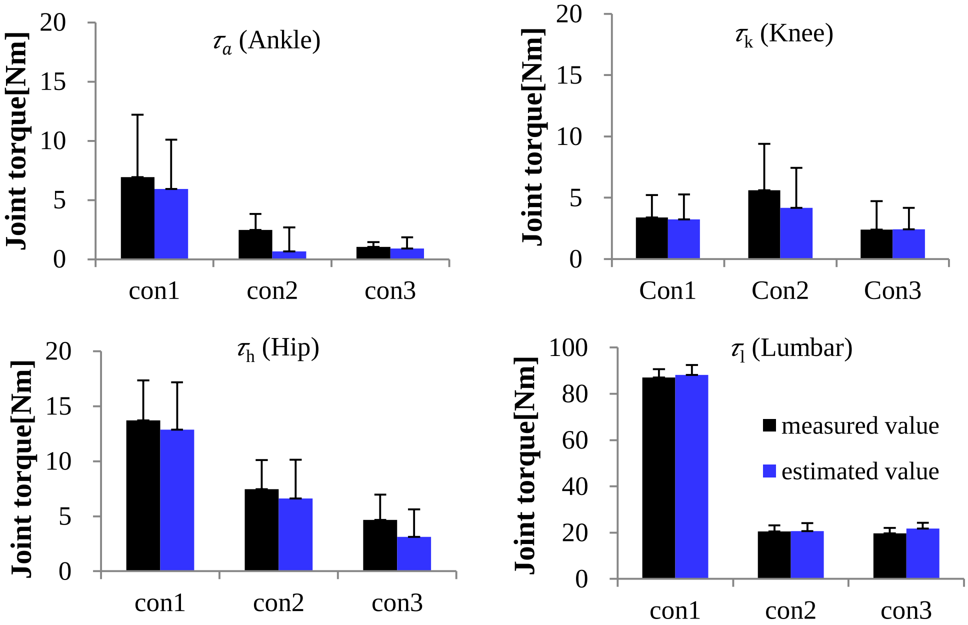

Fig. 9 Estimated joint torques and measured joint torques at each joints. Estimated values were coincident with measured values.

Table 4 Error of joint torques in percentage

	sub1	sub2	sub3	sub4	sub5
con1	0.10	0.10	0.03	0.09	0.26
con2	0.15	0.11	0.04	0.25	0.22
con3	0.15	0.11	0.22	0.17	0.23

among all the participants. These results suggested the validity of the estimation algorithm for soaking posture. Regarding the measured COP of the foot, only the toe and the heel were contacted with the bathtub surface in con1 and con2, with the exception of con3. It was probably because the ankle joint was dorsiflexed and exceeded 20 deg, which is the limitation of dorsiflexion, if the entire sole fitted with the wall of the bathtub (Yonemoto et al., 1995). These tendencies were also reproduced by estimated results, as shown in Fig. 7. The average values of the error in the location of the COP for each condition were 0.01 m or less, which was a good estimation result. However, the maximum error among all the participants was 0.064 m in the vertical direction at the back. This was due to the difference between the body surface at the back derived by spline interpolation based on the measured points of the trunk and the actual body surface affected. The errors of the estimated joint torques were less than 0.26 %. Furthermore, as shown in Fig. 9, the tendency of change in the joint torque between each condition was well reproduced. Judging from these results, it was possible to evaluate the joint torque of soaking postures in different bathtubs by using the algorithm in this study. Additionally, the joint torques in con2 were estimated using the coefficients k_0~ k_4 of the objective function among each participant determined from the measured results in con1 and con3. Thus, a result comparable to those in con1 and con3 was obtained. From this, it was thought that the estimation was possible for an arbitary bathtub, whose length L1 was between 1200 mm and 1600 mm, by determining the coefficients k_0~ k_4 based on the experiment for each participant in the range of these lengths.

In addition to the above, the validity of the algorithm to estimate the soaking posture and COP was verified by comparing the results with those of the incomplete algorithm. Fig. 10 shows a typical example of the estimated results calculated by the objective function, in which the term of the joint torques at the lumbar was removed. Compared with the measured results, the legs including the ankle joint, the knee joint and the hip joint were plantarflexed or extended. On the other hand, the lumbar was flexed and the trunk was upright. The lumbar spine was kyphosed, i.e. rounded back and sitting on the sacral bone, with a large load on the lumbar vertebra (Harrison et al., 1999, Castanharo et al., 2014). Therefore, it was considered that the soaking posture was actually determined to reduce both the load on the leg and the lumbar. Fig. 11 shows a typical example of results in con1 by the proposed objective function and by another incomplete objective function in which the term of the passive elastic joint torque at the metatarsal fibulare was removed. The estimated soaking posture of a foot using the incomplete objective function was more plantarflexed than the measured value. As a result, the angle between the foot side wall of the bathtub and the foot segment became large and the toes were largely extended. Meanwhile, since the estimated posture of the foot using the proposed objective function was dorsiflexed and came close to measured value, it was indicated that the human adjusted the soaking posture so as to make the toes less extended, resulting in a decrease in the passive elastic joint torque. From these results, the validity of the objective function considering not only the leg but the lumbar and the metatarsal fibulare was indicated. In addition, it was suggested that a human perceives the load on the whole body, which is from the upper body to the toe, and adjusts the soaking posture.

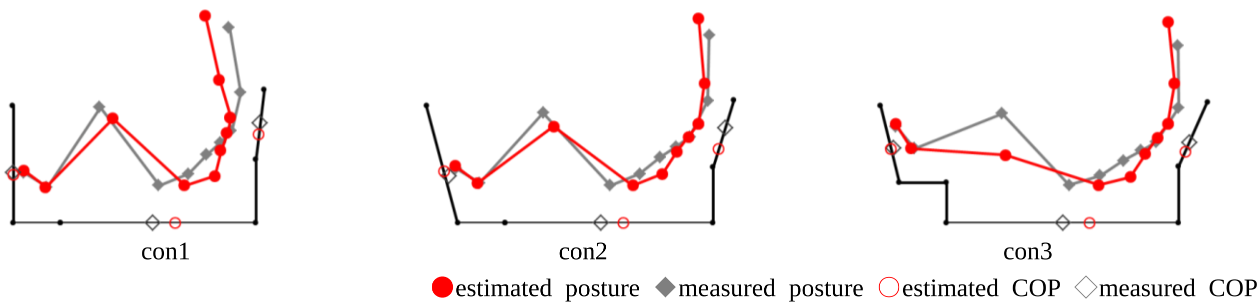

Fig. 10 Estimated results of soaking postures and COP without term of joint torque at the lumbar in objective function (Participant3). Estimated leg posture was more extension than measured one. On the other hand, estimated trunk posture was flexion at the lumbar.

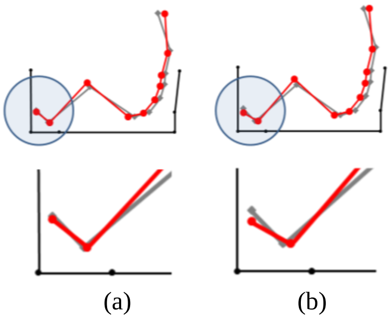

Fig. 11 Estimated results of soaking postures (above) and lower leg postures (bottom) (con1 and Participant4). (a) Posture was estimated using proposed objective function; (b) Posture was estimated without term of passive joint torque at the metatarsal in objective function. Ankle joint was more plantarflexed and metatarsal was more extended than the result of proposed objective function.

5. Conclusion

Based on the biomechanical model of the soaking posture developed in the previous study, we constructed an algorithm to estimate the soaking posture and the COP of the reaction forces. The algorithm was validated for the bathtub conditions, which covered the range of the general size in Japan. As a result, the soaking postures and COP were estimated with high accuracy. Furthermore, the validity of this algorithm was demonstrated by comparison with two types of incomplete algorithm. From the results of the present study, the possibility of a complete simulation, in which the joint torque can be estimated completely without experiments, is suggested. If the proposed algorithm for estimation of the soaking posture and COP can be combined with the previous algorithm for estimation of the reaction forces, such complete simulation will be realized. Furthermore, good results of the estimation were obtained by minimizing the objective function composed of the joint torques of the legs and at the lumbar as well as the passive elastic joint torque at the metatarsal fibulare. It suggested that a human had an unconscious strategy to determine the soaking posture in order to minimize the biomechanical load on a whole body as much as possible.

Moreover, it is expected that the model can be developed to simulate the soaking posture according to various races or bathtub size for overseas in the future, considering the difference in bathing style between domestic and overseas. It is also expected that a complete simulation model, which does not require an experiment, can be achieved to design a bathtub efficiently according to people in the target countries, if it becomes possible to derive the relationship between each coefficient of the objective function and factors such as preference of posture, physical constitution and race.

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