

# A Three-Dimensional Biomechanical Analysis of KOSHIWARI Exercise

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**Abstract:** The koshiwari (Sumo Squat) is a traditional exercise used for basic training for sumo wrestling, the national sport of Japan. This study compares and analyzes the kinetics and kinematics of the koshiwari and squat with wide-stance (WSQ) to provide insight related to the mechanical features of the koshiwari. Optical three-dimensional automatic analysis instruments were used to measure movements of 11 men during exercises. A force platform was used to measure floor reactions. Two movements were analyzed: koshiwari and WSQ. The koshiwari and WSQ were compared as analytical objectives, using paired *t*-tests corresponding to correction joint angles, angular impulse, and joint torques with the level of significance set under 5%. Koshiwari was found to involve markedly greater excursions of abduction (maximum and minimum angle, correction angle to 20%-60%) and external rotation (maximum and minimum angle, correction angle to 20%-60%) and external rotation angle 10%-90%) and torso forward tilt (maximum angle, correction angle 30%-100%). Koshiwari also involved greater extension-flexion axis, abduction-adduction axis, external rotation-internal rotation axis angular impulse and flexion (10%-100%), adduction (40%-60%), and external rotation (20%) torques at the hip than WSQ exercises. Results suggest that hip external rotation torque is attributable to hip external rotator muscle activity. The activity can apparently reduce the risk of ACL (Anterior cruciate ligament) injuries and patellofemoral pain syndrome and improve athletic performance.

Key words: Koshiwari exercise, sumo squat, hip joint, joint angle, joint torque.

# 1. Introduction

The koshiwari (Sumo Squat) is an exercise used in basic training for sumo wrestling, the national sport of Japan. Koshiwari requires that a person stand with feet shoulder-width apart, with externally rotated hip and feet pointed outwards and repeated extension and flexion movements of the knees and hips.

In Sumo competition, two sumo wrestlers face one another. The match finishes when either wrestler falls to the ground or is pushed out of bounds. The playing surface consists of sand, which makes wrestlers able to glide, but wrestlers must simultaneously lower the center of gravity to apply a driving force against an opponent. Therefore, it is important to apply tremendous force against the ground [1].

A wrestler must maintain abduction and external rotation of hips at the lowest position of koshiwari. Accordingly, koshiwari is regarded as an effective exercise to activate the muscles around the hip joints. Suhara et al. [2] reported from earlier studies that examined the muscle activities of healthy male adults that the gluteus maximus was highly activated at the lowest position of koshiwari. They concluded that the hip joint position contributes to activation.

Exercises to strengthen the gluteal muscles are important to prevent injury. Many studies have revealed weakness of the gluteal muscles as a risk factor of injuries of the lower extremities. Leetun et al. [3] examined 139 collegiate basketball players and other athletes, reporting that people who have hip abduction weakness and hip external rotation strength

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tend to have higher rates of injury of the lower extremities. Ireland et al. [4] compared a group of young females with history of patellofemoral pain syndrome and a group of healthy young females. The results showed that the former produced 26% less hip abduction strength and 36% less hip external rotation compared to healthy females. Zazulak et al. [5] examined the activation of gluteal muscles on the single-leg landing of male and female athletes at a National Collegiate Athletic Association (NCAA) division 1 college using electromyography, later reporting that females produced weaker activations of lower fibers of gluteal muscles. According to the findings, Zazulak et al. state that ACL injuries are preventable by improving the activation of lower fibers of gluteal muscles. Those studies demonstrate that gluteal muscle weakness causes malalignment of the lower extremities, which can constitute a risk factor for injuries on lower extremities.

Squat exercises are generally used for strengthening gluteal muscles when standing. Such exercises require a person to coordinate the flexion and extension movements on the hip, knee, and ankle joints. Many studies have examined squats of various types to improve the effects on activation of gluteal muscles, such as using heavier weights [6], plyometric movements [7], lower bottom position [8], and a wider stance [9]. Most such studies applied weights to subjects irrespective of heaviness. Few studies have tested subjects using body-weight exercises. In terms of difficulty of the movement, it is difficult to acquire correct movements of squat especially the beginners. Therefore, it can also be difficult to achieve proper activation of gluteal muscles. Squats are also known to provide adverse stress on knee joint with inappropriate movements [10]. Therefore, it is necessary to gain knowledge of how body-weight exercises exert effects on gluteal muscles in addition to those weighted exercises to provide other methods of training for those who have not acquired proper squat movements. Suhara et al. [2] reported that there greater external

rotation torque is exerted on the knee joint in body-weight squats in the comparison of kinetics of body-weight koshiwari to body-weight squat with a wide stance. Suhara reported that koshiwari might place less stress on knee joints because the knee joint is used mainly in the sagittal plane. Excessive torque applied in internal and external rotations damages ligaments and menisci of the knees. That earlier study, however, only examined the kinetics of the knee joint, ignoring state characteristics of kinetics and effects of koshiwari on gluteal muscles. Results of the present study might therefore provide important insights related to the kinetics of the knee and hip and effects of koshiwari on strengthening gluteal muscles. Consequently, the purpose of this study is to compare koshiwari and squat with a wide stance, which is known to provide greater activation of gluteal muscles and to provide insights into hip joint kinetics and kinematics.

# 2. Materials and Methods

## 2.1 Subjects

The study participants, for whom there is no history of severe trauma to the lower extremities, were 11 healthy men (age,  $20.18 \pm 0.57$  years; height,  $172.09 \pm$ 2.47 cm; weight,  $64.27 \pm 4.00$  kg) who reported no pain or difficulty of movement. We explained the purpose and procedures of the study to all participants and obtained their consent to participate in this study. This project was approved by the Research Ethics Committee of the University of Tsukuba.

# 2.2 Procedures

### 2.2.1 Experimental Tasks

The experimental tasks were the koshiwari and wide squat (WSQ). The koshiwari, as described by Suhara et al. [2], is a movement with hip and knee flexion and subsequent extension, with the descent stopping at  $90^{\circ}$  of knee flexion, so that the thighs are parallel to the floor. Also, the hips are in maximal external rotation. The trunk and lower legs are maintained as vertical.

The directions of the feet (angles of hip external rotation) are set at the greatest possible angles at which the subject can perform the task appropriately. In addition, a hand is set on the pelvis (Fig. 1a). The WSQ, as described by McCaw and Melrose [9], is a movement of flexion with subsequent extension with feet set apart at 140% of the shoulder width and pointed outward at  $15^{\circ}$  ( $15^{\circ}$  of hip external rotation). Lower extremity flexion and extension are performed with the trunk inclined anteriorly  $45^{\circ}$  relative to the floor. The knees are not displaced further forward than the toes, as

observed from the side, and the direction of each patella is aligned with the direction of the ipsilateral foot. In addition, the hand is set on the pelvis (Fig. 1b).

These tasks were performed with only the subject's own body weight as the load, and with each foot placed on a force platform. The excursion was maintained between  $0^{\circ}$  and  $90^{\circ}$  of knee flexion for both exercises. Each exercise was performed in synchrony to a metronome set at 60 beats/min, with one exercise repetition comprising descent for 2 s (early descending 1 s, late descending 2 s), remaining at the bottom for 1 s,



Time (%)

Fig. 1 Temporal sequence in a KOSHIWARI (SUMO Squat) exercise and Squat exercise with WSQ.

and ascent for 2 s (early ascending 1 s, late ascending 2 s). The total duration was 5 s. Two repetitions of the exercise were performed in succession with a 1-s interval between the repetitions. Experimental measurements were conducted after each subject had practiced the tasks for 2 weeks, being careful to perform them at uniform speed. Of the repetitions, the repetition with more uniform speed and reaching the proper angles was selected for analyses.

# 2.2.2 Collection and Analysis of Data

Three-dimensional coordinate data of the body (35 markers) were captured using a system with 12 cameras (250 Hz, Vicon-MX; Vicon Motion Systems, Ltd., Oxford, UK). Ground reaction forces of each leg were measured using force platforms (1,000 Hz, Kistler 9287B; Kistler Instruments AG, Winterthur, Switzerland). The coordinate data were smoothed using a Butterworth digital filter with zero phase shift set at optimal cutoff frequencies (2.5-12.5 Hz), as specified by Wells and Winter [11]. The exercises were performed slowly. Therefore, the ground reaction force data were downsampled to 250 Hz using a cubic spline function in MATLAB (The MathWorks Inc., Natick, MA).

## 2.3 Data Processing

2.3.1 Hip Joint Coordinate System and Trunk Angle To determine the joint coordinate systems, the hip joint center was estimated using a method advocated by the Clinical Gait Analysis Forum of Japan [12]. Centers of the knee and ankle joints were set at the midpoints between medial and lateral markers straddling the respective joints. The following describes how the joint (right-handed) coordinate systems were determined for the three joints of the lower right extremity.

In this study, the hip joint coordinate system was explained so that we emphasized descriptions of the hip joint kinematic and kinetic parameters. For the hip coordinate system, the following were set: zhip was a vector from the right knee joint center (knR) to the right hip joint center (hipR); yhip was the vector-product of the zhip and a vector from the left hip joint center (hipL) to the hipR; xhip was the cross-product the yhip and the zhip (Fig. 2a). Functionally, the following were set: xhip was the extension (+) and flexion (-) axis; yhip axis was the abduction (+) and adduction (-) axis; and zhip was the external rotation (+) and internal rotation (-) axis.

The hip joint angle was established using Euler angles, based on Roy et al. [13]. The order of rotation at hip joint was x-y-z: three degrees of freedom at the hip in the order of extension, abduction, and external rotation.

The torso angle, positive for torso forward tilt, was defined as the angle between the vertical z-axis and a position vector from the midpoint between the two hip joints to the midpoint (clavC) between the superior border of the sternum (clav) and the seventh cervical vertebra (c7) (positive values: torso forward tilt) (Fig. 2b).

In addition, to correct the difference by the joint angle in the initial position by the calculated joint angle, we subtracted a joint angle of 1% as the correction joint angle.

2.3.2 Lower-Extremity Joint Torques

With the coordinate systems for three segments (foot, shank, and thigh) of both legs established, the angular velocities of the segments were calculated by differentiating the temporal histories of the unit vectors of the axes in the coordinate systems. Mass, center of gravity, and moments of inertia were calculated for each segment using body-segment parameters provided by Ae [14]. The forces and moments around the three joints were calculated by application of the inverse dynamics approach to the coordinate data of the body and the ground reaction force data of both legs. Then the hip joint torque was converted by projecting the joint moment onto the hip joint coordinate system explained above. In addition, the torque was divided by the subject's body weight to eliminate the influence of different absolute body dimensions. The angular impulse



Fig. 2 Definition of hip joint coordinate system and vector of the longitudinal axis for the trunk segment.

|                           |         | KOSHIWARI          | SQUAT                |
|---------------------------|---------|--------------------|----------------------|
| Ext + / Flex -            | Maximum | $51.89 \pm 6.04$   | $85.88 \pm 7.68 * *$ |
|                           | Minimum | $2.32 \pm 10.32$   | $0.14 \pm 12.84$     |
| Abd + / Add -             | Maximum | 50.17 ± 7.96*      | 30.14 ± 6.51         |
|                           | Minimum | 20.39 ± 3.92*      | $12.42 \pm 2.69$     |
| Ext ro + / Int ro -       | Maximum | 43.2 ± 12.31*      | $15.52 \pm 8.92$     |
|                           | Minimum | $27.72 \pm 10.69*$ | $1.2 \pm 8.77$       |
| Forw tilt + / Back tilt - | Maximum | $17.89 \pm 2.41$   | 22.11 ± 3.24**       |
|                           | Minimum | $12.81\pm2.18$     | $11.3 \pm 1.3$       |

 Table 1
 Comparison of the Hip joint angle between KOSHIWARI and WSQ (deg: correction before angle).

Values are mean  $\pm$  SD; \* Indicates that KOSHIWARI is greater than WSQ (p < 0.05); \*\* Indicates that WSQ is greater than KOSHIWARI (p < 0.05); Ext + / Flex -: Extension + / Flexion -; Abd + / Add -: Abduction + / Adduction -; Ext ro + / Int ro -: External rotation + / Internal rotation -; Forw tilt + / Back tilt -: Torso forward tilt + / Torso backward tilt -.

was calculated by integrating the torque of all frames, as described below.

2.3.3 Time Normalization and Sectioning

The tasks performed for this study were analyzed beginning from the moment that descent was initiated and ending at the moment that ascent was completed. The time series of data from the beginning to end of each task was normalized such that the end occurred at 100%, with data to be analyzed at 10% intervals.

#### 2.4 Statistical Analyses

All values are expressed as mean  $\pm$  standard deviation. Statistical procedures were performed using SPSS Statistics 22 for Windows (IBM, Tokyo, Japan) with the level of significance set below 5%. Measurements taken during the koshiwari and WSQ were compared using paired *t*-tests at the angular

impulse, for all 11 phases, from 0%-100% of task completion for each correction joint angle and joint torque parameter. Moreover, results were corrected *p*-values using Bonferroni method. No statistical analysis was implemented to compare one phase to the other in the same experimental task.

# 3. Results

#### 3.1 Kinematics

Table 1 presents a comparison of the maximum and minimum joint angle of hip joint between koshiwari and WSQ (correction before joint angle). Regarding hip extension and the flexion angle, the angle in WSQ is significantly greater than the angle in koshiwari at the maximum hip flexion. No significant difference was found between the two exercises for minimum hip flexion. Regarding the hip abduction and adduction angle, koshiwari produced a significantly larger angle than WSQ did at the maximum hip abduction. Koshiwari produced a significantly greater angle than WSQ did at the minimum hip abduction. Regarding to the hip external rotation and internal rotation, koshiwari produced a significantly greater joint angle than WSQ did at the maximum hip external rotation. Koshiwari produced a significantly greater angle than WSQ did with minimum hip external rotation.

Fig. 3a presents a comparison of the correction joint angle of hip joint between koshiwari and WSQ (correction joint angle). Regarding hip extension and flexion, WSQ has significantly greater hip flexion than



Fig. 3 Comparing of hip joint torque (a) and correction hip joint angle (b) between KOSHIWARI and WSQ. Solid lines—KOSHIWARI, Broken lines—WSQ; Ext—Extension, Flex—Flexion; Abd—Abduction, Add—Adduction; Ext ro—External Rotation, Int ro—Internal Rotation; Forw tilt—Forward Tilt, Back tilt—Backward Tilt; \*p < 0.05. Values are means ± SQ.



Fig. 4 Comparison of the angular impulse of hip joint between KOSHIWARI and WSQ (Nm•s/kg). \*p < 0.05. Values are means  $\pm$  SD.

koshiwari from the 10%-90% phase. Regarding hip abduction and adduction. koshiwari produced significantly greater hip abduction than WSQ from the 20%-60% phase. For hip external rotation and internal rotation, no significant difference was found. Regarding the torso forward and backward tilt, WSQ produced significantly greater torso forward tilt than koshiwari did from the 30%-100% phase. In addition, initial angle hip flexion is  $(5.47 \pm 7.44)$ , hip abduction  $(23.35 \pm 5.04)$ , hip external rotation  $(39.33 \pm 10.04)$ , torso forward tilt (13.32  $\pm$  2) of koshiwari and hip flexion (0.14  $\pm$  7.68), hip abduction (13.1  $\pm$  2.68), hip external rotation (24.76 ± 7.41), torso forward tilt  $(11.14 \pm 1.48)$  of WSQ.

# 3.2 Kinetics

Fig. 4 presents a comparison of the angular impulse of the hip joint associated with koshiwari and WSQ. Koshiwari produced significantly greater angular impulse than WSQ did about the axis on extension and flexion. Koshiwari produced a significantly greater angular impulse than WSQ did about the axis on abduction and adduction. Koshiwari produced significantly greater angular impulse than WSQ did about for the axis on external and internal rotation.

Fig. 3b shows hip joint torques for koshiwari and WSQ. Regarding extension and flexion torque, koshiwari produced significantly greater flexion torque than WSQ did from the 10%-100% phase. For abduction and adduction torque, koshiwari produced significantly greater hip adduction torque than WSQ did from the 40%-60% phase. For external and internal rotation torque, koshiwari produced significantly greater hip external torque than WSQ did at the 20% phase.

## 4. Discussion

#### 4.1 Hip Joint Kinematics and Kinetics

In this study, koshiwari was found to produce higher angular impulse at the axis of external and internal rotation of the hip than WSQ. Time-series data show that koshiwari and WSQ produced hip external rotation torque. Especially at the 20% phase, it was significantly higher for koshiwari than WSQ. Consequently, the angular impulse in koshiwari consists of hip external rotation torque; it is greater for koshiwari, especially during the descending phase. Regarding time-series data of the correction joint angle, the hip external rotation angle was smaller in both exercises as the participants decreased their height. It is reasonable to infer that the gluteus maximus and deep external rotators are contracted eccentrically because the angle of hip external rotation was reduced, even though hip external rotation torque was found for the descending phase for those two exercises.

Neuman [15] reported that the hip external rotation angle decreases as the hip flexion angle increases. The present study revealed that the hip flexion angle reached a maximum value at the phase of 50% and that the hip external rotation angle becomes minimal. Accordingly, results of this study suggest that koshiwari produces greater hip external rotation torque than WSQ does, with greater activation of muscles for hip external rotation because it requires maintenance of hip external rotation, which is normally reduced as the hip joint flexes.

Koshiwari produced greater angular impulse at the axis of abduction and adduction of the hip than WSO did. Time-series data of joint torque show that both exercises produced adductor torque at the hip joint, but koshiwari has significantly greater torque at the phase from 30%-60% than WSQ does. Consequently, this angular impulse resulted from the hip adduction torque, which is greater in koshiwari, especially at the descending phase and the hold phase. Additionally, in both exercises, time-series data show that the correction hip abduction angle increases from the descending phase to the hold phase. Therefore, koshiwari requires the use of hip adductors such as the adductor longus and magnus eccentrically because the hip abduction angle increases, although the hip adduction torque increases.

Delmore et al. [16], however, reported that activation of the adductor longus is minimal. That

study compared muscle activations among some exercises generally used for the hip joint. Sumo squat has only 13% Maximum voluntary isometric contraction (MVIC) on the adductor longus. Suzuki [17] reported that muscle activation of the adductor longus in koshiwari and WSQ were not significantly different. According to the two studies, the muscle activation of adductor muscles does not contribute greatly to the hip adductor torque in koshiwari. Neumann [15] described that hip adductor muscles are the restricting tissue for at the end of the range of hip abduction. Robertson et al. [18] reported that the sum of all tissues becomes one joint torque. For analysis of motion occurring closer to the end range of the joint, muscle extensibility becomes the major contributor to joint torque.

For koshiwari, this study revealed that the hip adductor torque became greatest at the 40% phase and the hip abduction angle reached approximately  $50^{\circ}$  (correction before joint angle), which is regarded as the end range of hip abduction. Therefore, the hip adductor muscle extensibility contributes to the hip adductor torque in koshiwari.

This study revealed that koshiwari produced higher angular impulse at the axis of flexion and extension of the hip than WSQ did. Koshiwari, as shown by time-series data, produced flexion torque constantly, but WSQ produced flexion torque only at 1%, 10%, 20%, 90%, and 100% of phase and extension torque from the 40%-80% phase. Neuman [15] studied characteristics of mechanics of the static standing posture. The center of gravity is located slightly posterior from the center of hip joints, so hip flexion torque maintains the standing posture. For koshiwari, hip flexion torque becomes maximal at the 0% phase and becomes minimal at the hold phase. Therefore, the actual motion of hip flexion does not increase hip flexion torque because the torque is produced to maintain the standing posture. In WSQ, the hip flexion torque is produced at the descending phase. Hip extension torque is produced from the late descending phase to the ascending phase. Manabe et al. [19] studied the kinetics of squat motions related to different techniques. They reported that hip extension torque becomes greater as the torso tilts further forward. The present study also demonstrated that WSQ has larger forward tilt of torso than koshiwari from 30%-100% phase in which hip extension torque is produced. Therefore, the forward tilt of the torso strongly influences the production of hip extension torque at the late descending phase to the early ascending phase in WSQ.

# 4.2 Practical Applications

Results obtained from this study demonstrate that koshiwari produces greater activation of hip external rotators than WSQ does. Sahrmann [20] describes tibiofemoral rotation with valgus (TFRVal), which is regarded as a typical malalignment of the knee joint, as the causative alignment for acute knee injuries such as ACL injuries [21], chronic knee injuries such as patellofemoral pain syndrome [22], and iliotibial band syndrome [23]. Patients with TFRVal perform partial-depth squats with adducted and internally rotated hip joint and valgus knee joint. Koshiwari is an effective exercise to alleviate this malalignment, which is caused mainly by weak hip external rotators and abductors, because it activates hip external rotators. It can reduce the risk of ACL injuries and patellofemoral pain syndrome.

After studying baseball pitchers, Hirayama et al. [24] reported that faulty mechanics of the lower extremities slow ball speed by reducing the hip extension torque of the leading leg (left leg of a right-handed pitcher) as the number of pitches increases. Hirayama also described the possible effectiveness of koshiwari to increase the activation of gluteal muscles at a flexed hip angle, while not reducing the hip extension torque and not degrading pitching performance.

Koshiwari activates hip external rotators. Results of the present study showed that the participants produced hip external rotation torque while lowering their center of gravity, especially from the late descending phase to the early ascending phase. Therefore, koshiwari can be an effective exercise for sumo and for various sports that require athletes to lower the body.

## 4.3 Implications for Future Research

This study specifically conducted analysis of the kinematics and kinetics of koshiwari and WSO by examining joint torques to predict muscle activation around joints with the inverse dynamics assumption. Some other muscles that have not been examined deeper and closer to the joint surface, such as deep external rotators and typically piriformis and iliopsoas, are important arthrokinematically. A simulation such as Software for Interactive Musculoskeletal Modeling (SIMM) is expected to be effective for safe analysis of deep muscles in the hip joint. Consequently, with the assistance of the simulation, it is necessary to examine characteristics of koshiwari-related mechanics. Simultaneously, it is important to assess the applications of koshiwari for athletes and for the general population to clarify the effectiveness of koshiwari.

## **5.** Conclusion

The results unveiled in this work are shown below. Koshiwari was found to involve markedly greater excursions of abduction and external rotation at the hip compared with the WSQ, as well as markedly less hip flexion and torso forward tilt. Koshiwari also involved greater extension-flexion axis, abduction-adduction axis, external rotation-internal rotation axis angular impulse and flexion, adduction, and external rotation torques at the hip than WSQ exercises.

## References

- Kuwamori, S., Kondo, M., and Touno, T. 1998. "Effects of Attaching Weight Load to Body on 'DEASHI' (Dashing Forward) Power in SUMO Wrestlers—A Simulation Study of Body Fat Increase." *Research Journal* of BUDO 30 (3): 1-9. (in Japanese)
- [2] Suhara, H., Shiraki, H., and Miyakawa, S. 2014.
   "Biomechanical Analysis of KOSHIWARI Exercise." Japanese Journal of Clinical Sports Medicine 22 (1):

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128-37. (in Japanese)

- [3] Leetun, D., Ireland, M., Willson, J., Ballantyne, B., and Davis, I. 2004. "Core Stability Measures as Risk Factors for Lower Extremity Injury in Athletes." *Med. Sci. Sports Exerc.* 36 (6): 926-34.
- [4] Ireland, M., Willson, J., Ballantyne, B., and Davis, I. 2003.
  "Hip Strength in Females with and without Patellofemoral Pain." J. Orthop. Sports Phys. Ther. 33 (11): 671-6.
- [5] Zazulak, B., Ponce, P., Straub, S., Medvecky, M., Avedisian, L., and Hewett, T. 2005. "Gender Comparison of Hip Muscle Activity during Single-Leg Landing." J. Orthop. Sports Phys. Ther. 35 (5): 292-9.
- [6] Manabe, Y., Yokozawa, T., and Ogata, M. 2003. "Effect of Load Variation on Lower Muscle Activity and Joint Torque during Parallel Squats." *Jpn. J. Phys. Fitness Sports Med.* 52 (1): 89-98. (in Japanese)
- [7] Manabe, Y., Yokozawa, T., Shimada, K., and Ogata, M. 2004. "Effect of Speed Variation and Stretch-Shortening Cycle on Lower Muscle Activity and Joint Torque during Parallel Squat." *Jpn J. Phys. Fitness Sports Med.* 53 (4): 425-42. (in Japanese)
- [8] Caterisano, A., Moss, R., Pellinger, T., Woodruff, K., Lewis, V., Booth, W., and Khadra, T. 2002. "The Effect of Back Squat Depth on the EMG Activity of 4 Superficial Hip and Thigh Muscles." *J. Strength Cond. Res.* 16 (3): 428-32.
- [9] McCaw, S., and Melrose, D. 1999. "Stance Width and Bar Load Effects on Leg Muscle Activity during the Parallel Squat." *Medicine & Science in Sports & Exercise* 31 (3): 428-36.
- [10] Escamilla, R. 2001. "Knee Biomechanics of the Dynamic Squat Exercise." *Med. Sci. Sports Exerc.* 33 (1): 127-41.
- [11] Wells, R., and Winter, D. 1980. "Assessment of Signal Noise in the Kinematics of Normal, Pathological and Sporting Gaits." *Human Locomotion* 1 (1): 92-3.
- [12] Kurabayashi, J., Mochimaru, M., and Kawauchi, M. 2003.
  "Validation of the Estimation Methods for the Hip Joint Center." *Society of Biomechanisms Japan* 27 (1): 29-35. (in Japanese)
- [13] Roy, B., Sylvia, O., Dennis, T., and James, R. 1991. "A Gait Analysis Data Collection and Reduction Technique." *Human Movement Science* 10 (5): 575-87.

- [14] Ae, M. 1996. "Body Segment Inertia Parameters for Japanese Children and Athletes." Jpn. J. Sports Sci. 15 (3): 155-62. (in Japanese)
- [15] Neumann, D. 2005. Kinesiology of the Musculoskeletal System. Translated by Shimada, T. Tokyo: Ishiyaku Publishers, Inc.
- [16] Delmore, R., Laudner, K., and Torry, M. 2014. "Adductor Longus Activation during Common Hip Exercises." J. Sport Rehabil. 23 (2): 79-87.
- [17] Suzuki, T. 2004. The Study of the Electromyographic Analysis of KOSHIWARI Exercise. Tokyo: University of Tsukuba Press. (in Japanese)
- [18] Robertson, G., Caldwell, G., Hamill, J., Kamen, G., and Whittlesey, S. 2004. *Research Methods in Biomechanics*. Translated by Ae, M. Tokyo: Taishukan Publishing Co., Ltd.
- [19] Manabe, Y., Yokozawa, T., and Ogata, M. 2004. "Effect of Movement Variation on Lower Limb Muscle Activity and Joint Torque during Squat." *Jpn. J. Phys. Fitness Sports Med.* 53 (3): 321-36. (in Japanese)
- [20] Sahrmann, S. 2013. Movement System Impairment Syndromes of the Extremities, Cervical and Thoracic Spines. Translated by Takei, H. Tokyo: Ishiyaku Publishers, Inc.
- [21] Hewett, T., Myer, G., Ford, K., Heidt, R., Colosimo, A., Mclean, S., Bogert, A., Paterno, M., and Succop, P. 2005.
  "Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes: A Prospective Study." Am. J. Sports Med. 33 (4): 492-501.
- [22] Dierks, T., Manal, K., Hamill, J., and Davis, I. 2008. "Proximal and Distal Influences on Hip and Knee Kinematics in Runners with Patellofemoral Pain during a Prolonged Run." J. Orthop. Sports Phys. Ther. 38 (8): 448-56.
- [23] Noehren, B., Davis, I., and Hamill, J. 2007. "ASB Clinical Biomechanics Award Winner 2006 Prospective Study of the Biomechanical Factors Associated with Iliotibial Band Syndrome." *Clin. Biomech.* 22 (9): 951-6.
- [24] Hirayama, D., Fujii, N., Koike, S., and Ae, M. 2010. "The Changes on Mechanical Work of the Lower Limb Joints during Baseball Pitching in a Simulated Game." *Jpn. J. Phys. Fitness Sports Med.* 59 (2): 225-32. (in Japanese)

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