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Influence of simulated hip muscle weakness on hip joint forces during deep squatting

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ABSTRACT

This study aimed to determine the effects of simulated hip muscle weakness on changes in hip joint forces during deep squat motion. Ten healthy individuals performed squat motion at three different positions (0° foot angle [N-squat], 10° toe-in [IN-squat], and 30° toe-out [OUT-squat]). A scaled musculoskeletal model for each participant was used to calculate the muscle and hip joint forces. For each hip muscle, models of full strength, mild muscle weakness (15% decrease), and severe muscle weakness (30% decrease) were created. The muscles affecting the hip joint forces were identified, and the rate of change in the joint forces was compared among the three squat conditions. The anterior hip joint force was increased in the muscle weakness models of the inferior gluteus maximus (iGlutMax) and iGlutMax+deep external rotator (ExtRot) muscles. With 30% muscle weakness of these muscles, statistically significant differences in the rate of increase in the anterior joint force were observed in the following order: IN-squat (iGlutMax, 29.5%; iGlutMax+ExtRot, 41.4%), N-squat (iGlutMax, 18.3%; iGlutMax+ExtRot, 27.8%), and OUT-squat (iGlutMax, 5.6%; iGlutMax+ExtRot, 9.3%). OUT-squat may be recommended to minimize the increase in hip joint forces if accompanied by hip muscle weakness.

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KEYWORDS
Musculoskeletal model; gluteus maximus; deep external rotator muscles; groin pain

Introduction

Groin pain is a common problem associated with various athletic activities (de SA et al., 2016; Sedaghati et al., 2013). Although groin pain is multifactorial, the causes are classified into defined clinical entities such as adductor-related, hip-related, and other conditions that cannot be easily classified (Weir et al., 2015). Hip-related groin pain originates from the hip joint, including femoroacetabular impingement (FAI) and labral tears (Weir et al., 2015).

Deep bilateral squat has been used as a functional test for FAI as squat requires hip hyperflexion and provokes groin pain (Ayeni et al., 2014). However, biomechanical alterations, including hip and pelvic kinematics, in patients with groin pain and FAI, are inconsistent. While a previous study reported that patients with FAI showed decreased hip flexion angle with increased pelvic posterior tilt during squat motion compared with healthy participants (Catelli et al., 2018), a few others found no difference in hip flexion angle with decreased pelvic posterior tilt (Bagwell et al., 2016; Lamontagne et al., 2009) or decreased hip internal rotation (Bagwell et al., 2016). Moreover, maximum squat did not show any difference in pelvic and hip angles, even though the ipsilateral pelvis rise and hip adduction were increased in patients with FAI in squat with limited pelvic and trunk compensation (Diamond et al., 2017). This inconsistency of findings suggests the difficulty of extracting risk factors for hip-related groin pain from the biomechanical alterations of squat motion.

Although not yet verified in squat motion, partial weakness of the hip muscles alters the magnitude and direction of hip joint force during hip strength exercise owing to the compensatory increase of muscle force in other synergistic muscles (Lewis et al., 2009). Patients with groin pain and FAI commonly have hip impairments such as muscle weakness and reduced range of motion (Diamond et al., 2015; Freke et al., 2016; Kloskowska et al., 2016; Ryan et al., 2014). According to a recent report on soccer players, there were patients with hip-related groin pain (impingement-type symptom) despite the absence of abnormal hip morphology (King et al., 2018). Moreover, weaker hip extension muscle strength has been observed in symptomatic patients with cam morphology compared to asymptomatic patients with the same morphology (Catelli et al., 2018). Collectively, hip muscle weakness may affect hip-related groin pain as well as bony deformity during motion, such as the squat.

However, the verification of the causal relationship between muscle weakness and change in hip joint force during motion is difficult by measurement in patients with groin pain. The mechanical stress and symptoms in the hip joint are not always owing to hip impairments such as muscle weakness, which may also be caused by pain and continuous compensatory motion. The caudal relationship of changes in muscle force on that in joint force can be estimated by computational simulation using a musculoskeletal model. The knee and hip joint forces have been validated by the musculoskeletal model using the same software used in this study, even the deep squat motion (Kang et al., 2018; Van Houcke et al., 2020).

Furthermore, hip joint forces during squats can be affected by different hip positions. An increase in strain on the anterior labrum has been confirmed especially in hip flexion, adduction,

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and internal rotation in a cadaver experiment (Safran et al., 2011). In patients with FAI and asymptomatic volunteers, labral tears and cartilaginous defects of the acetabulum and femur are commonly observed in the anterosuperior and superior regions (Tresch et al., 2017). Considering that the translation force can cause load on the acetabular labrum (Lertwanich et al., 2016), it is also important to determine the hip position in squats that are prone to increase hip joint forces, especially the anterior and superior joint forces.

Therefore, this study aimed to determine the effects of hip muscle weakness on changes in hip joint force during squat motion at different hip positions. It secondarily investigated the dynamics of compensatory muscle force changes in other muscles concerning muscle weakness in a particular hip muscle in the same squat motion. Since the gluteus maximus and deep hip external rotator muscles are the primary muscles used in squatting motions (Diamond et al., 2019; McCurdy et al., 2018), the weakness of these muscles was hypothesized to change the hip joint forces. We also hypothesized that weakness of these muscles is compensated for by the hamstrings and the vastus muscles, which act cooperatively with the gluteus maximus in supporting body weight (Zajac et al., 2003). The addition of knowledge on the relationship between muscle weakness and changes in hip joint force would aid in the understanding of the underlying mechanism of hip-related groin pain and provide insight into the identification of muscles to strengthen in patients with groin pain.

Material and methods

Participants

A total of 10 healthy participants (five females and five males; age, 25.2 ± 4.0 years; height, 167.0 ± 7.2 cm; mass, 60.6 ± 8.9 kg) volunteered to participate in this study. Exclusion criteria included any disease, symptoms, and history of surgery in the lower extremity/spinal joints and any other conditions affecting independent movement. Written informed consent was obtained from each participant, and the protocol was approved by the institutional ethics committee.

Data acquisition

Participants were clothed in close-fitting shorts and T-shirts, and reflective markers were attached to the body according to the Vicon Plug-in-gait full-body marker set (Davis et al., 1991). The markers were attached either directly to the skin or onto the clothing at the following locations: the anterolateral and posterolateral aspects of the head, seventh cervical spinous process, tenth thoracic spinous process, jugular notch, xiphoid process, acromioclavicular joints, lateral epicondyles, medial and lateral sides of the wrists, second metacarpal heads, anterior superior iliac spines, posterior superior iliac spines, lateral aspect of the shank and thigh, lateral femoral condyles, calcanei, lateral malleolus, and second metatarsal heads. Clothing near markers on the anterior superior iliac spines was taped to avoid hiding the markers by clothing during movement.

After 5 min warm-up using the bicycle ergometer, the participants performed squat movements under the three conditions: squat with hip neutral position (N-squat), with hip adducted position (IN-squat), and with hip abducted position (OUT-squat) (Figure 1). Before recording the data, the depth and foot position during the squat was determined for each participant. Squat depth was defined as the posture where the thigh was parallel to the floor. Alternatively, if the posterior thigh and shank were contacted at this position, squat depth was defined as the maximum depth at which they did not contact since their contact could influence the calculated joint contact forces on the lower extremity (Wu et al., 2019). A thin rod was placed posteroinferior to the participant as feedback for the buttocks to touch lightly at the deepest position during squatting (Figure 1). The distance between both heels in squat tasks was defined as the distance between the left and right anterior superior iliac spines. The foot angle was 0°, 10° toe-in, and 30° toe-out for N-, IN-, and OUT-squat conditions, respectively. The foot angle was defined as the angle formed by the antero-posterior axis and the line through the middle of the heel and second toe. The participants were asked to flex the knee towards the second toe in each condition. Another thin rod was placed at the position of the toes as a guide so that the knee did not move forward to the toes during squatting (Figure 1). The anterior tilt of the trunk was allowed to maintain postural balance during a squat, and both hands were placed on the abdomen. After several practices, squat movements were repeated five times consecutively for each squat condition. From the standing position, the participant descended in 3

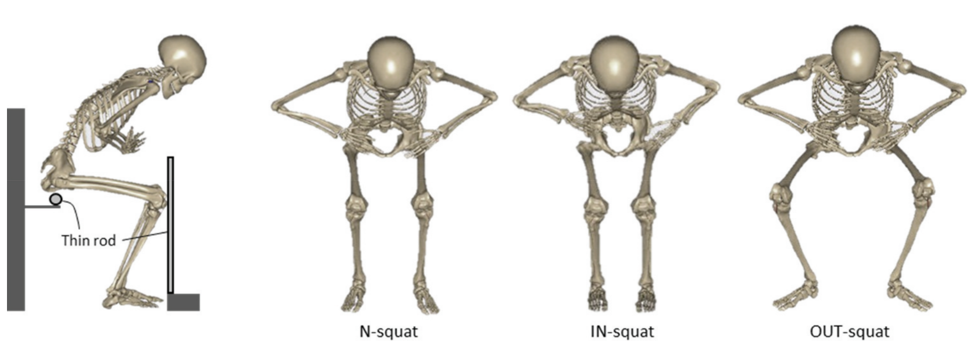

Figure 1. Settings for performing squat movement (Left). Squat movement with hip neutral position at foot angle of 0°(N-squat), with hip adducted position at foot angle of 10°toe-in (IN-squat), and with hip abducted position at foot angle of 30°toe-out (OUT-squat).

s, rested at the deepest position for 1 s, and ascended in 3 s paced with an electronic metronome. The three conditions were randomly measured. The middle three of the five consecutive trials were extracted as input data to the musculoskeletal model.

The marker position and ground reaction forces were collected using an 8-camera VICON motion system (Vicon Motion Systems Ltd., Oxford, England) and force plates (Kistler Japan Co., Ltd. Tokyo, Japan) at sampling rates of 100 Hz and 1,000 Hz, respectively. The maker position data and ground reaction force data were filtered using a fourth-order Butterworth low-pass filter at 6 Hz.

Musculoskeletal model

For estimating the hip joint forces and muscle forces, we used the Twente Lower Extremity Model version 2 included in the Mocap Lower Body model in Anybody Modelling System v.7.1 (AnyBody, Aalborg, Denmark) (Figure 2). The model is based on anatomical data produced from a cadaver study (Carbone et al., 2015), with the modifications including wrapping definition of the gluteus maximus muscle have been made to improve the accuracy of joint force estimation (De Pieri et al., 2018). The model contains the following 11 segments: pelvis, both sides of femurs, patellae, shanks, talus, and feet. A total of eight joints providing 12 degrees of freedom (DOFs) are included: the hip joint is modelled as spherical (3 DOFs), and knee, talocrural, and subtalar joints are modelled as hinges (1 DOF). There are no additional DOFs from the patellae. The model of each lower limb contains 55 muscles, and divided into 169 elements. The muscle elements were modelled by Hill's model, consisting of contractile and elastic elements.

First, we created a scaled musculoskeletal model for each participant based on anthropometric data. A linearly scaling model, which is a standard method in this software, was used as the scaling method. The linearly scaling method relies on the markers' data during the squat movement to linearly scale the segment length and width and calibrate the marker positions (Lund et al., 2015). Second, kinematic analysis was performed using the scaled model and marker trajectories to compute joint angles during squats. After kinematic optimization, the resultant joint kinematics and ground reaction forces were used to drive the inverse dynamic analysis model to compute the muscle forces and hip joint forces. For muscle forces, a numerical optimization procedure with a third-order polynomial muscle recruitment criterion was utilized. We analysed the hip joint forces and muscle forces for the right leg of participants normalized by body weight (BW). The muscle and joint forces were calculated for all three trials in each condition, and the mean values of the three trials were used for the analysis.

Data analysis

Based on previous studies reporting that hip muscle strength in patients with groin pain or FAI is approximately 10%–35% lower than that in healthy individuals (Casartelli et al., 2011; Frasson et al., 2020; Harris-Hayes et al., 2014; Kloskowska et al., 2016), simulations were performed under three conditions of each muscle for each squat task: full-strength simulation (without muscle weakness), mild muscle weakness (15% decrease), and severe muscle weakness (30% decrease). In the muscle weakened models, before inverse dynamics analysis, muscle volume was modified by 15% and 30% decrease of the original muscle volume against the following muscle for exploring the effects of each muscle volume on hip internal contact force, separately: superior and inferior gluteus maximus (sGlutMax and iGlutMax), anterior and posterior gluteus medius (aGlutMed and pGlutMed), anterior, middle, and posterior gluteus minimus, semitendinosus (ST), semimembranosus (SM), biceps femoris long head (BF), distal, middle, and proximal adductor magnus, gracilis (Grac), adductor longus (AddLong), psoas major, iliacus, rectus femoris, sartorius, tensor fasciae latae, deep external rotator muscles (ExtRot) including piriformis, obturator internus and externus, gemellus superior and inferior, and quadratus femoris, and combined iGlutMax and ExtRot (iGlutMax+ExtRot).

Statistical analysis

A sample size calculation using GPower 3.1.7 (Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany) utilizing the data investigating the simulated changes in hip muscle forces and hip joint forces during gait (C.A. Myers et al., 2019) indicated that a sample size per group of seven was necessary to achieve a power of 0.8, with an alpha level of 0.016.

The Shapiro-Wilk test confirmed that all dependent variables were normally distributed. Peak hip joint angle and forces of three dimensions in the full-strength model were compared among the three squat conditions by using a linear mixed

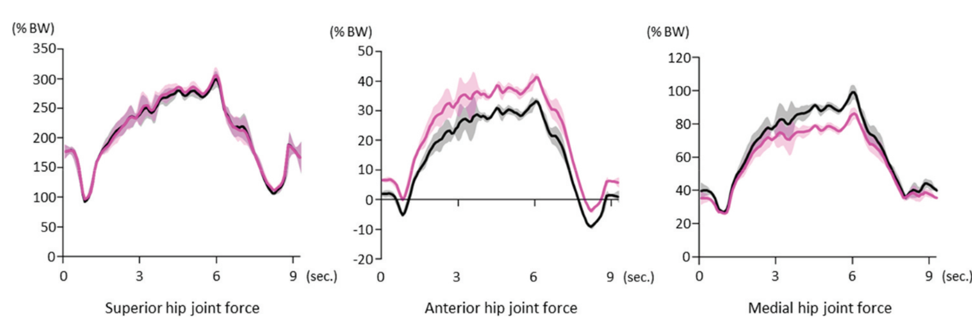

Figure 2. Typical waveforms of hip joint forces (mean ± standard deviation of three trials in one participant) during In-squat. The black line indicates the full-strength model, and the red line represents 30% decrease in the superior gluteus maximus + the deep external rotator muscle model.

model (LMM) with post hoc comparison with Holm correction. The LMM is suitable for the analysis of repeated measurements because it involves fixed effects and random effects and is recommended over classic repeated measures analysis of variance Kwon et al., 2014). Peak hip joint forces were also compared among the three squat types using LMM with Holm correction with adjustment of peak hip flexion angles. For identifying the muscle weakness affecting changes in hip joint forces, hip joint forces were compared between muscle weakened models (15% and 30% decrease) to the full-strength model for each muscle in three squat conditions using LMM with Holm collection. Given the clinical significance, a change in the hip joint force of less than 5% was excluded. If a common muscle affecting hip joint force for the three squat conditions was observed, the rate of change in hip joint force owing to muscle weakness was compared using LMM with Holm collection. Furthermore, to identify the compensatory mechanism for muscle weakness, the change in muscle forces of other muscles in the muscle weakened model affecting changes in hip joint force were compared between the full-strength and muscle weakened models using LMM with Holm collection. The muscles showing less than 5% changes in muscle force were excluded. All statistical tests were performed using SPSS version 26.0 (IBM Japan Ltd., Tokyo, Japan). The significance level was set at $P < 0.05$.

Results

Typical waveforms of hip joint forces are illustrated in Figure 2, and the peak hip joint angle and forces in the full-strength model during the three squats are described in Table 1. The hip flexion angle was slightly larger in the OUT-squat than in the N- and IN-squat. There was no statistically significant difference in hip joint forces among the three squats with and without adjusting the hip flexion angle.

The rate of change in hip joint forces is shown in Figure 3 only for conditions in which the change was 5% or more and a statistically significant change compared with the full-strength condition. In N-squat, a 15% decrease in iGlutMax and iGlutMax+ExtRot and a 30% decrease in iGlutMax, ExtRot, and iGlutMax+ExtRot increased the anterior joint force compared with the full-strength condition. In IN-squat, 15% and 30% decrease in iGlutMax and iGlutMax+ExtRot, respectively increased the anterior joint force. The 30% decrease in iGlutMax, iGlutMax+ExtRot, and aGlutMed increased the anterior joint force in the OUT-squat. Conversely, a decrease in medial joint force was observed, especially in the ExtRot and iGlutMax+ExtRot weakened models. Regarding the superior joint force, no significant change was observed except that the 30% decrease in iGlutMax+ExtRot increased by 8.5% for superior joint force in IN-squat.

The compensatory changes of muscle forces in other muscles in the iGlutMax and iGlutMax+ExtRot weakened models are illustrated in Figure 4. In the iGlutMax weakened model, the muscle force was increased in the sGlutMax (3.7–9.5%BW), ST (3.9–9.9%BW), SM (2.3–4.7%BW), BF (1.8–4.9%BW), ExtRot (2.-7–12.2%BW), and vasti muscles (2.5–16.7%BW). The pattern of muscle force changes in the iGlutMax+ExtRot weakened model was similar to that of the iGlutMax weakened model. The muscle force was increased in the sGlutMax (4.2–11.3%BW), ST (3.9–11.1%BW), SM (2.4–5.2%BW), BF (2.0–6.5%BW), and vasti muscles (2.6–17.4%BW). No muscle was found showing 5% or more and a statistically significant change in the ExtRot weakened model.

Discussion

In all three squat conditions, the anterior joint force increased in the iGlutMax and iGlutMax+ExtRot weakened models, supporting the research hypothesis. The rate of increase in the

Table 1. Summary of peak hip joint angle and force during squats.

	N-squat	IN-squat	OUT-squat	*P*-value† (Cohen's *d*)	*P*-value† adjusted for hip flexion angle (Cohen's *d*)
Hip joint angle (degrees)					
Flexion	96.8 ± 6.2	94.8 ± 7.1	100.2 ± 5.7	N vs IN: 0.133 (0.30) **N vs OUT: 0.024 (0.53)** **IN vs OUT: 0.001 (0.83)**	–
Adduction	−5.5 ± 2.4	2.1 ± 2.8	−23.5 ± 4.0	**N vs IN: <0.001 (2.39)** **N vs OUT: <0.001 (9.19)** **IN vs OUT: <0.001 (6.80)**	–
Internal rotation	−0.6 ± 2.4	5.7 ± 2.9	−12.8 ± 4.5	**N vs IN: <0.001 (1.85)** **N vs OUT: <0.001 (3.60)** **IN vs OUT: <0.001 (5.44)**	–
Hip joint force (% body weight)					
Superior direction				N vs IN: 0.102 (0.79)	N vs IN: 0.057 (0.90)
Raw data	271.6 ± 24.2	307.0 ± 33.4	288.6 ± 65.1	N vs OUT: 0.498 (0.38)	N vs OUT: 0.581 (0.20)
Data adjusted by hip flexion angle	272.8 ± 43.1	312.6 ± 44.6	281.8 ± 45.3	IN vs OUT: 0.498 (0.41)	IN vs OUT: 0.176 (0.70)
Anterior direction				N vs IN: 0.194 (0.34)	N vs IN: 0.548 (0.23)
Raw data	22.3 ± 10.4	18.8 ± 9.5	26.9 ± 11.0	N vs OUT: 0.182 (0.45)	N vs OUT: 0.548 (0.27)
Data adjusted by hip flexion angle	22.5 ± 11.1	19.9 ± 11.4	25.6 ± 11.6	IN vs OUT: 0.173 (0.79)	IN vs OUT: 0.240 (0.50)
Medial direction				N vs IN: 1.000 (0.19)	N vs IN: 1.000 (0.27)
Raw data	93.7 ± 12.0	99.3 ± 15.3	108.1 ± 47.8	N vs OUT: 0.867 (0.48)	N vs OUT: 1.000 (0.34)
Data adjusted by hip flexion angle	94.3 ± 29.3	102.3 ± 30.1	104.6 ± 30.4	IN vs OUT: 1.000 (0.30)	IN vs OUT: 1.000 (0.08)

Values are expressed as mean ± standard deviation. †*P*-value in linear mixed model with Holm correction. Bold indicates statistically significant difference.

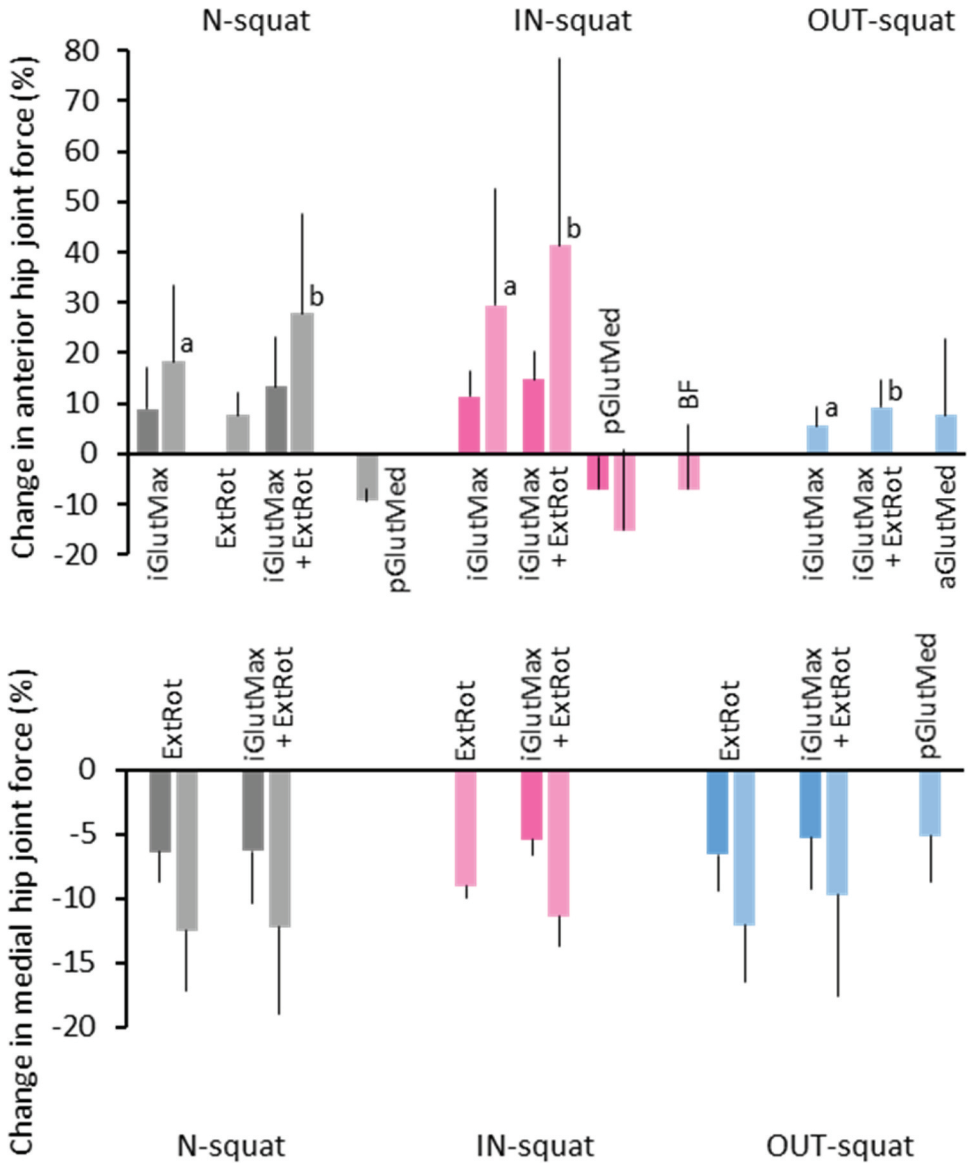

Figure 3. Change in hip joint forces (mean and SD) in muscle weakened model. Rate of changes in anterior (upper) and medial (lower) hip joint forces due to the muscle weakness showing 5% or more and statistically significant change compared with the full-strength condition. The dark and light colors of gray, blue, and red indicate 15% and 30% decreased conditions in each squat, respectively. (a): Difference in 30% decrease in iGlutMax (N- vs. IN-squat, $P = 0.012$, $d = 0.93$; N- vs. OUT-squat, $P = 0.010$, $d = 1.06$; IN- vs. OUT-squat, $P < 0.001$, $d = 1.99$). (b): Difference in 30% decrease in iGlutMax+ExtRot (N- vs. IN-squat, $P = 0.030$, $d = 0.75$; N- vs. OUT-squat, $P = 0.008$, $d = 1.03$; IN- vs. OUT-squat, $P < 0.001$, $d = 1.78$). iGlutMax = Inferiro gluteus maximus; ExtRot = deep external rotators; iGlutMax+ExtRot = combined iGlutMax and ExtRot; pGlutMed = posterior gluteus medius; aGlutMed = anterior gluteus medius; BF = biceps femoris.

anterior joint force owing to these muscle weaknesses was highest in the IN-squat and lowest in the OUT-squat. The vasti muscles, hamstrings, sGlutMax, and ExtRot (only in the iGlutMax weakened model) compensatory increased muscle forces in response to the decrease in iGlutMax and iGlutMax +ExtRot weakness. Although the increase in muscle force of the vasti muscles was similar in all three squat conditions, muscle weakness tended to be compensated by sGlutMax and BF in the IN-squat and ST in the OUT-squat. Moreover, the medial joint force was decreased in the ExtRot and iGlutMax+ExtRot weakened models. To the best of our knowledge, this is the first report to demonstrate the relationship between partial muscle weakness of the hip muscles and changes in hip joint forces during deep squats. The findings can provide clinical suggestions on the squat method for avoiding excessive hip joint loading, particularly anterior joint force, in individuals with hip muscle weakness.

The resultant hip joint force measured in vivo using implants in patients with hip arthroplasty during squat was reported to have an average of 231% body weight (Bergmann et al., 2016). This value is lower than our simulated resultant hip joint force of approximately 288% of the body weight in N-squat. However, since the in vivo experiment defined "knee bend" in standing as a squat, the extent of hip flexion and anterior trunk lean is unknown. Moreover, the knee flexion angle of 73° in the in vivo experiment was smaller than the average knee flexion angle of 91° in the present study. The squat with knee restriction used in the present study increases hip loading over

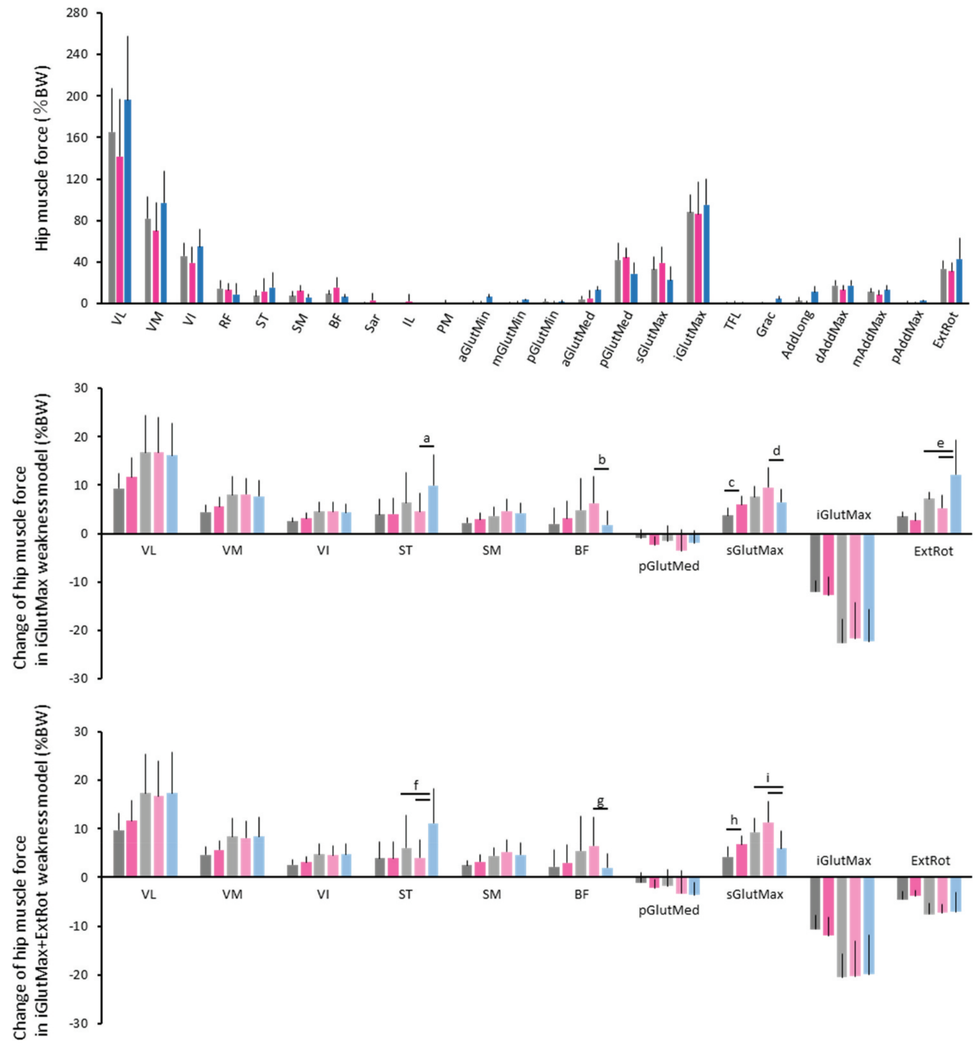

Figure 4. Muscle forces (mean and SD) in the full-strength model (top) and change of the muscle forces showing 5% or more change than the full-strength model in iGlutMax weakened model (middle) and iGlutMax+ExtRot weakened model (bottom). The gray, red, and blue indicate N-, IN-, and OUT-squat, and dark and light colors indicate 15% and 30% decreased conditions in each squat, respectively. (a): Difference between IN- and OUT-squat ($P = 0.016$, $d = 1.10$). (b): Difference between IN- and OUT-squat ($P = 0.028$, $d = 0.97$). (c): Difference between N- and IN-squat ($P = 0.015$, $d = 0.85$). (d): Difference between IN- and OUT-squat ($P = 0.003$, $d = 1.18$). (e): Difference between N- and OUT-squat ($P = 0.007$, $d = 1.38$) and IN- and OUT-squat ($P < 0.001$, $d = 1.91$). (f): Difference between N- and OUT-squat ($P = 0.028$, $d = 0.97$) and IN- and OUT-squat ($P = 0.003$, $d = 1.36$). (g): Difference between IN- and OUT-squat ($P = 0.042$, $d = 0.91$). (h): Difference between N- and IN-squat ($P = 0.026$, $d = 0.80$). (i): Difference between N- and OUT-squat ($P = 0.007$, $d = 1.09$) and IN- and OUT-squat ($P < 0.001$, $d = 1.74$). VL = vastus lateralis; VM = vastus medialis; VI = vastus intermedius; RF = rectus femoris; ST = semitendinosus; SM = semimembranosus; BF = biceps femoris long head; Sar = sartorius; IL = iliacus; PM = psoas major; aGlutMin, mGlutMin, and pGlutMin = anterior, middle, and posterior gluteus minimus; aGlutMed and pGlutMed = anterior and posterior gluteus medius; sGlutMax and iGlutMax = superior and inferior gluteus maximus; TFL = tensor fasciae latae; Grac = gracilis; AddLong = adductor longus; dAddMax, mAddMax, and pAddMax = distal, middle, and proximal adductor magnus; ExtRot = deep external rotators; iGlutMax+ExtRot = combined iGlutMax and ExtRot.

unrestricted squats that mainly involve knee flexion (Lorenzetti et al., 2012). Considering these differences, the hip joint force estimated in this study is acceptable.

In the iGlutMax and iGlutMax+ExtRot weakened models, compensatory increases in muscle forces were observed in the vasti muscles and hamstrings in addition to sGlutMax. The vasti muscles showed the highest muscle force during the squat movement. They are uniarticular knee extensors, and the muscle forces mainly contribute to knee extension. However, the action of the vasti muscles can rotate the femoral segment anteriorly and accelerate the hip joint into extension simultaneously with knee extension (Zajac et al., 2003). Thus, the vasti muscles would have compensated for the decrease in hip extension in the iGlutMax and iGlutMax+ExtRot weakened models. Similarly, the hamstrings would increase their muscle forces to compensate for hip extension weakness. The decrease in hip external rotation owing to the weakness of iGlutMax and iGlutMax+ExtRot may have been primarily covered by the sGlutMax.

Changes in the balance of hip muscle forces in the iGlutMax and iGlutMax+ExtRot weakened models increased anterior hip joint force during the squat. As the anterior rotation of the femur owing to the vasti muscles causes the proximal femur to be displaced anteriorly, the increase in vasti muscle force can induce an increase in the anterior joint force (Zajac et al., 2003). Although the muscle force was smaller than that of the vasti, the increase in muscle force of the sGlutMax and hamstrings, particularly in BF, was larger in IN-squat. These could be the factors increasing the anterior joint force in the iGlutMax and iGlutMax+ExtRot weakened models in IN-squat. Moreover, the medial joint force was decreased in the ExtRot and iGlutMax +ExtRot weakened models. Although no common muscle compensation pattern was found in the ExtRot weakened model, muscle weakness of the ExtRot, common in these muscle-weakened models, reduces hip medial joint force, that is, the force that presses the femoral head into the acetabulum. The increase in the anterior joint force and decrease in the medial joint force indicates that the direction of the vector of the resultant of the hip joint forces was altered anteriorly in the horizontal plane.

Cadaver experiments have shown that resection of the labrum or tear of both the iliofemoral ligament and labrum increases anterior translation of the femoral head during hip joint movement (C. A. Myers et al., 2011; Lertwanich et al., 2016). This implies the role of the labrum in resisting the anterior translation of the femoral head; alternatively, an excessive anterior joint force could lead to an increase in labral stress and damage. Considering that labral pathology is one of the major causes of hip-related groin pain (Weir et al., 2015), increased anterior hip joint force may be the underlying cause of such pain. In contrast, squat with decreased muscle force of the ExtRot caused a decrease in the medial hip joint force, and an adequate amount of medial joint force is essential for joint stability. Although this is not due to the actions of muscles, disruption of the capsular sealing increases the displacement of the femoral head during hip movement, causing hip instability (Crawford et al., 2007). Thus, the decrease in medial joint force owing to the weakened ExtRot observed in this study may encompass inadequate hip stability. This pathological mechanism may also contribute to groin pain, as hip instability produces hip-related groin pain (Reiman et al., 2020).

From a clinical point of view, IN-squat should be avoided for individuals with groin pain with iGlutMax and ExtRot muscle weakness since anterior and superior joint forces tend to increase. Additionally, the hip position of flexion, adduction, and internal rotation imposes a strain on the groin (Safran et al., 2011). Conversely, OUT-squat has a relatively small effect on increasing hip joint force even if accompanied by muscle weakness, and thus it may be recommended for individuals with iGlutMax and ExtRot muscle weakness, to start with OUT-squat. Since squats are representative means of strengthening lower-extremity muscles, they are generally used in individuals with muscle weakness. Moreover, the participants are instructed to strictly control the position of the lower extremity and trunk according to the purpose of the exercise (Schoenfeld, 2010). Therefore, the results obtained by the inverse dynamic analysis in the musculoskeletal model, that is, the analysis with the assumption of the same movement despite the muscle weakness, could be generalized to the problems related to actual squat exercise in individuals with hip muscle weakness.

This study has some limitations that warrant discussion. First, we simulated only muscle force reduction as a factor affecting hip joint forces. Factors such as muscle pain, fatigue, and tightness also influence squat performance (Cheatham et al., 2018). The lower hip joint range of motion (tightness) is recognized as a risk factor for groin pain (Tak et al., 2017), and patients commonly combine the clinical features of pain, muscle weakness, and tightness. Therefore, further examination of the complex involvement of these related factors in hip joint force may contribute to the elucidation of the clinical condition of hip-related groin pain. Second, we used a musculoskeletal modelling approach to predict hip joint forces during squatting. Increased joint force can predict increased tissue pressure in the relevant direction; however, analysis of stress dynamics in bone and soft tissue may require the finite element method. Third, we did not record electromyography (EMG) in this study. However, the muscle activity patterns in the model during squatting and similar lifting movements have been validated in comparison with the recorded EMG in previous studies (Kang et al., 2019; Mirakhorlo et al., 2014; Stambolian et al., 2016). Additionally, although we used a commonly used optimization algorithm for muscle force estimation (Trinler et al., 2019), different algorithms may change the results obtained, such as muscle forces and joint contact forces. Finally, we acknowledge that the present study only involved healthy adult individuals. For example, FAI syndrome was defined as a motion-related clinical disorder of the hip (Griffin et al., 2016). Thus, some patients with FAI and groin pain may have altered squat movement. Moreover, altered femoral geometry can affect hip joint forces (Kainz et al., 2020). Further research is required to analyse changes in hip joint force using patient-specific musculoskeletal models.

In conclusion, we performed an analysis of hip joint forces during squat motions at three different hip angles using a musculoskeletal model. The superior, anterior, and medial hip joint forces were not significantly different among the three squat conditions. The anterior hip joint force increased in the iGlutMax and iGlutMax+ExtRot weakened models for all three squat conditions, and the rate of increase of anterior joint force was high in the order of IN-, N-, and OUT-squats. Muscle weakness of the iGlutMax and iGlutMax+ExtRot muscles was compensated mainly by the increase in muscle forces of the vasti muscles, hamstrings, and sGlutMax. Meanwhile, the medial hip joint force was decreased in the ExtRot and iGlutMax +ExtRot weakened models in the three squats. These findings may partially explain the underlying mechanism of hip-related groin pain in patients with hip muscle weakness. Clinically, OUT-squat may be recommended to prevent excessive anterior joint force over IN-squat in patients at the risk of groin pain with muscle weakness of iGlutMax and ExtRot. Moreover, muscle strength exercise of the ExtRot might contribute to maintaining the medial joint force in the hip joint during squat.

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List of abbreviations of muscles

Superior gluteus maximus = sGlutMax
Inferior gluteus maximus = iGlutMax
Anterior gluteus medius = aGlutMed
Posterior gluteus medius = pGlutMed
Anterior gluteus minimus = aGlutMin
Middle gluteus minimus = mGlutMin
Posterior gluteus minimus = pGlutMin
Semitendinosus = ST
Semimembranosus = SM
Biceps femoris long head = BF
Distal adductor magnus = dAddMax
Middle adductor magnus = mAddMax
Proximal adductor magnus = pAddMax
Gracilis = Grac
Adductor longus = AddLong
Psoas Major = PM
Iliacus = IL
Rectus femoris = RF
Sartorius = Sar
Tensor fasciae latae = TFL
Deep external rotator muscles = ExtRot
Vastus lateralis =VL
Vastus medialis = VM
Vastus intermedius = VI

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