The difference in passive tension applied to the muscles composing the hamstrings - comparison among muscles using ultrasound shear wave elastography

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Abstract

Background: Hamstring muscle strain is one of the most common injuries in sports. Therefore, to investigate the factors influencing hamstring strain, the differences in passive tension applied to the hamstring muscles at the same knee and hip positions as during terminal swing phase would be useful information. In addition, passive tension applied to the hamstrings could change with anterior or posterior tilt of the pelvis.

Purpose: The aims of this study were to investigate the difference in passive tension applied to the individual muscles composing the hamstrings during passive elongation, and to investigate the effect of pelvic position on passive tension.

Methods: Fifteen healthy men volunteered for this study. The subject lay supine with the angle of the trunk axis to the femur of their dominant leg at 70° and the knee angle of the dominant leg fixed at 30° flexion. In three pelvic positions ("Non-Tilt", "Anterior-Tilt" and "Posterior-Tilt"), the shear elastic modulus of each muscle composing the hamstrings (semitendinosus, semimembranosus, and biceps femoris) was measured using an ultrasound shear wave elastography

Results: The shear elastic modulus of semimembranosus was significantly higher than the others. Shear elastic modulus of the hamstrings in Anterior-Tilt was significantly higher than in Posterior-Tilt.

Conclusion: Passive tension applied to semimembranosus is higher than the other muscles when the hamstring muscle is passively elongated, and passive tension applied to the hamstrings increases with anterior tilt of the pelvis.

Key words: hamstrings, pelvis, shear wave elastography

Introduction

Hamstring muscle strain is one of the most common injuries in sports (Bishop and Fallon, 1999, Brooks et al., 2006, Ekstrand et al., 2011, Feeley et al., 2008, Gabbe et al., 2006) and results in considerable time lost from training and competition (Brooks and Fuller, 2006, Ekstrand and Hagglund, 2011). Many studies have investigated the risk factors and epidemiological features of hamstring muscle strain to identify preventive measures. Some have suggested that hamstring muscle strain is particularly likely to occur during the terminal swing phase of sprinting (Heiderscheit et al., 2005, Schache et al., 2009). The biceps femoris is the most commonly injured muscle among the hamstring muscles (Koulouris et al., 2007, Verrall et al., 2003). A previous study (Thelen et al., 2005) using a computer simulation reported that the percentage change in the length of the biceps femoris muscle tendon unit from standing upright to the terminal swing phase during running was higher than that of the semitendinosus and semimembranosus muscles, and this has been considered one of the reasons for some of the epidemiological features of hamstring muscle strain.

An ultrasound technology, ultrasound shear wave elastography, has enabled us to noninvasively and reliably measure the muscle shear elastic modulus (Bercoff et al., 2004). Previous studies have reported a strong linear relationship between the shear elastic modulus measured using ultrasound shear wave elastography and the passive muscle tension (Chernak et al., 2013, Koo et al., 2013, Maisetti et al., 2012). Therefore, the shear elastic modulus measured using ultrasound shear wave elastography was used as an index of the indirect passive tension. Using this technique, our previous study (Umegaki et al., 2015) reported that the passive tension applied to the semimembranosus was the highest among those applied to the hamstring muscle components at 45° knee flexion and 90° hip flexion. To reveal the cause of this inconsistency, it is important to investigate the in vivo differences in the passive tension applied to the muscles composing the hamstring at the same knee and hip positions as during the terminal swing phase.

The increases in the passive tension applied to the hamstring muscles and in hamstring muscle strain occur mostly during the terminal swing phase of sprinting, in which the hamstring muscle is greatly elongated, in accordance with the hip flexion and knee extension seen in this phase (Chumanov et al., 2011, Yu et al., 2008). If the increase in passive muscle tension during this phase is an important factor in hamstring muscle strain, an anterior or a posterior tilt of the pelvis should likewise be an important factor affecting the passive tension applied to the hamstrings, considering that the hamstring muscles originate from the ischial tuberosity (Abebe et al., 2009). In addition, although the hip joint angle, which is defined as the angle of the trunk with respect to the femur, remains the same, it is possible that the anterior or posterior tilt of the pelvis is different. Therefore, we hypothesized that an anterior tilt of the pelvis can increase the passive tension applied to the hamstring muscles at the same hip joint angle. However, to the best of our knowledge, no study has investigated the effect of pelvic tilt on the passive tension applied to the hamstring muscles.

The aims of this study were to investigate the differences in the passive tension applied to the individual muscles (semitendinosus, semimembranosus, and biceps femoris) composing the hamstrings during passive elongation with the knee and hip angles simulating those seen during the terminal swing phase, and to investigate the effect of pelvic tilt on the passive tension by measuring the shear elastic modulus.

Methods

Subjects

Fifteen healthy males (age, 22.6 ± 1.4 years; height, 172.7 ± 3.8 cm; weight, 68.1 ± 5.0 kg) volunteered for this study. Subjects with a history of neuromuscular disease or musculoskeletal injury involving their lower limbs were excluded from the study. In addition, the subjects recruited were participants in recreational sports but not in any strength or flexibility training at the time of the study. All subjects were fully informed of the procedures and purpose of the study, and then written informed consent was obtained from all of them. This study was approved by the ethics committee of the Kyoto University Graduate School and the Faculty of Medicine.

Experimental procedure

Each subject lay supine on a bed with their trunk kept horizontal. The lower leg on the dominant side was attached to a dynamometer (Biodex system 4.0, Biodex Medical Systems Inc., USA). The angle between the trunk axis and the femur (trunk–femur angle) of their dominant leg was fixed at 70°, measured using a regular goniometer, and the knee angle was fixed at 30° flexion, because these angles most closely match the angles in which the hamstrings are maximally elongated during the terminal swing phase of running (Thelen and Chumanov, 2005). The subject's knee axis was adjusted to coincide with the rotating axis of the dynamometer. The non-dominant femur was fixed to the bed using a belt to maintain a constant hip angle of the non-dominant leg. In pelvic alignment, the neutral pelvic position was defined as "Non-Tilt," and anterior and posterior tilt positions of the pelvis with respect to Non-Tilt were defined as "Anterior Tilt" and

“Posterior Tilt,” respectively (Fig. 1). The pelvis was tilted by placing a wedge between the pelvis and the bed. In these three positions, the shear elastic modulus, passive knee flexion torque, and joint angle were measured.

Joint angle

A schematic representation of the measurement of the joint angle is shown in Fig. 2. The subjects were fitted with 25-mm reflective markers located on the anterior superior iliac spine (a), the midpoint (b) between the anterior superior iliac spine and the posterior superior iliac spine, the greater trochanter (c), and the lateral femoral epicondyle (d) on the dominant side facing the camera (iVIS HF M43, Canon, Japan). Two reflective markers (e and f) were fitted on the bed’s edge. The line that linked the two markers on the bed’s edge (e and f) was defined as the trunk axis; the line that linked the markers at (a) and (b) was defined as the pelvic axis, and the line that linked the markers at (c) and (d) was defined as the femur axis. We defined the angle of the femur axis with respect to the trunk axis as the trunk–femur angle (T–F angle) and the angle of the femur axis with respect to the line perpendicular to the pelvic axis as the pelvis–femur angle (P–F angle). Pictures of the three pelvic positions were acquired using a camera positioned 3 m from the sagittal side of the subjects. Moreover, the T–F and P–F angles were quantified three times for each position using open-source digital measurement software (Image J, NIH, USA) on the pictures, and their mean values were used for further analysis. The interclass correlation coefficients [ICC (1, 3)] were high for the T–F angle (Anterior Tilt: 0.930, Non-Tilt: 0.879, Posterior Tilt: 0.965) and for the P–F angle (Anterior Tilt: 0.959, Non-Tilt: 0.961, Posterior Tilt: 0.945).

Measurement of the shear elastic modulus

The shear elastic moduli of the semitendinosus, semimembranosus, and biceps femoris muscle bellies on the dominant leg were measured at three points: the midpoints of the thigh from the greater trochanter to the medial epicondyle of the thighbone for the semitendinosus and semimembranosus, and the lateral epicondyle of the thighbone for the biceps femoris, as confirmed by palpation and B-mode imaging. These points were marked before measurement. The shear elastic moduli of the semitendinosus, semimembranosus, and biceps femoris were measured using ultrasound shear wave elastography (Axiplorer; SuperSonic Imagine, Aix-en-Provence, France). An ultrasound transducer (50-mm-long SL-15-4 linear ultrasound transducer) was positioned on the marked points parallel to the directions of the muscle fibers for the semitendinosus, semimembranosus, and biceps femoris, which were confirmed by tracing several fascicles without interruption across the B-mode image (Fig. 3). This apparatus measured the shear wave speed (m/s), and the shear elastic modulus (G) was calculated from the shear wave propagation speed (V) using the following equation:

$$G = \rho V^2$$

where ρ is the muscle mass density, which is presumed to be 1000 kg/m^3 (Gennisson et al., 2005, Nakamura et al., 2014, Nordez et al., 2008). The shear elastic moduli of the semitendinosus, semimembranosus, and biceps femoris were measured twice, and their mean values were used for further analysis. The intraclass correlation coefficients (1, 1) of the shear elastic modulus were high in the semitendinosus (Anterior Tilt: 0.917, Non-Tilt: 0.971, Posterior Tilt: 0.862), semimembranosus (Anterior Tilt: 0.976, Non-Tilt: 0.965, Posterior Tilt: 0.963), and biceps femoris (Anterior Tilt: 0.99, Non-Tilt: 0.975, Posterior Tilt: 0.989). A previous study (Nakamura et al., 2014) reported that stretching for >2 min decreased muscle stiffness. Therefore, in this study, measurement in each position took <10 s, which is short enough not to affect muscle stiffness. The measurements were performed in a random order to exclude the effect of the measurement time.

Passive knee flexion torque

Using the Biodex, the knee angle was fixed at 30° flexion, and the passive knee flexion torque and shear elastic modulus were simultaneously measured for 10 s. Before measurement, the effect of gravity on the passive torque measurement was excluded. The mean value for the 3 s following the first 3 s from the start of measurement was used to extract the steady torque. The passive torque was measured thrice at the same pelvic position, and the mean values were used for further analysis. The ICCs (1, 3) of the passive torque were high in Anterior Tilt (0.881), Non-Tilt (0.929), and Posterior Tilt (0.926).

Statistical analysis

Statistical analysis was performed using SPSS (version 18.0, SPSS Japan Inc., Tokyo, Japan). For the joint angle and passive knee flexion torque, a one-way repeated measures analysis of variance (one-way ANOVA) was used to determine the differences among the three pelvic positions. When a significant main effect was observed, the differences among the three positions were determined using Bonferroni's post hoc test.

For the shear elastic modulus of the semitendinosus, semimembranosus, and biceps femoris, two-way ANOVA [muscle group (semitendinosus, semimembranosus, and biceps femoris) × three pelvic positions (Anterior Tilt, Non-Tilt, and Posterior Tilt)] was used to investigate the interactions between each muscle group and pelvic position. One-way ANOVA was used to determine the differences in the muscle groups and the three pelvic positions. When a significant main effect was observed, the differences between muscle groups and the three positions were determined using Bonferroni's post hoc test. Differences were considered statistically significant at an alpha level of 0.05.

Results

Joint angle

The results for the T–F and P–F angles are shown in Table 1 as mean ± SD (standard deviation). For the T–F angle, one-way ANOVA indicated no significant main effect of the three pelvic positions ($F = 0.04$, $p = 0.961$). On the other hand, for the P–F angle, one-way ANOVA indicated a significant main effect of the three pelvic positions ($F = 21.9$, $p < 0.01$). Bonferroni's post hoc test indicated that the P–F angle was significantly larger in Anterior Tilt than in Non-Tilt and Posterior Tilt, and the P–F angle was significantly larger in Non-Tilt than in Posterior Tilt.

Shear elastic modulus

The results for the shear elastic modulus are shown in Table 2 as mean ± SD. Two-way ANOVA [muscle group (semitendinosus, semimembranosus, and biceps femoris) × three pelvic positions (Anterior Tilt, Non-Tilt, and Posterior Tilt)] indicated no significant interaction ($F = 2.01$, $p = 0.085$). For each muscle group and the three pelvic positions, one-way ANOVA indicated a significant main effect of the muscle group ($F = 43.7$, $p < 0.01$) and the three pelvic positions ($F = 33.0$, $p < 0.01$). For the muscle groups, Bonferroni’s post hoc test indicated that the shear elastic modulus of the semimembranosus was significantly higher than that of the semitendinosus and biceps femoris in all pelvic positions, and that of the biceps femoris was significantly higher than that of the semitendinosus in Anterior Tilt. In the three pelvic positions, Bonferroni’s post hoc test indicated that the shear elastic moduli of the semitendinosus, semimembranosus, and biceps femoris increased significantly with an anterior tilt of the pelvis, with the exception of semitendinosus between Anterior Tilt and Non-Tilt, and that of the biceps femoris between Non-Tilt and Posterior Tilt.

Passive knee flexion torque

The results for the passive knee flexion torque are shown in Table 3 as mean ± SD. One-way ANOVA indicated a significant main effect of the three pelvic positions ($F = 20.9$, $p < 0.01$). Bonferroni’s post hoc test indicated that the passive knee flexion torque was significantly larger in Anterior Tilt than in Non-Tilt and Posterior Tilt, and significantly larger in Non-Tilt than in Posterior Tilt.

Discussion

Comparison among muscles

In this study, we investigated the differences in the passive tension applied during passive elongation to the individual muscles (semitendinosus, semimembranosus, and biceps femoris) composing the hamstring muscle by measuring the shear elastic modulus in vivo. Previous studies have reported a strong linear relationship between the shear elastic modulus measured using ultrasound shear wave elastography and the passive muscle tension (Chernak and DeWall, 2013, Koo and Guo, 2013, Maisetti and Hug, 2012). Therefore, in this study, the shear elastic modulus measured using ultrasound shear wave elastography was used as an index of the indirect passive tension. The shear elastic modulus of the semimembranosus was significantly higher than that of the semitendinosus and biceps femoris in all pelvic positions. This result is consistent with our previous study (Umegaki et al., 2015) and also suggests that the passive tension applied to the semimembranosus is the highest among those applied to the three biarticular muscles composing the hamstring muscle at the same knee and hip angles as in the terminal swing phase.

In a study using a computer simulation (Thelen and Chumanov, 2005), the semitendinosus, semimembranosus, and biceps femoris were elongated up to almost 108.2%, 107.5%, and 110%, respectively, of the length in the upright standing position during the terminal swing phase. Considering these results, it was thought that the elongation rate of the semimembranosus in the current study would be the smallest among those of the three biarticular muscles composing the hamstring muscles, so the shear elastic modulus would be lowest in the semimembranosus, but this is inconsistent with the results of the current study. However, the elongation rate of a muscle is just one of the factors causing passive tension, and an important factor in hamstring muscle strain is tension itself. Therefore, considering the shear elastic modulus results in this study, it is suggested that the semimembranosus might be the most commonly injured among the hamstring muscles during passive muscle elongation. Previous studies have reported that the biceps femoris is the most commonly injured hamstring muscle during sprinting (Koulouris and Connell, 2007, Verrall and Slavotinek, 2003), but hamstring muscle strain occurs particularly during the terminal swing phase of sprinting, not only because of its passive elongation but also because of the high intensity of the contraction (Thelen and Chumanov, 2005) that occurs during this phase. On the other hand, the results of this study, which show that the passive tension applied to the semimembranosus is the highest among those applied to all the hamstring muscles, support a previous study (Askling et al., 2008), which reported that, among the muscles composing the hamstring muscles, the semimembranosus is the most commonly injured during passive muscle elongation, for example, during dance or stretching. The muscle in which the highest passive tension is applied is not the same as the muscle that is elongated most among the hamstring muscles. This may be because the semimembranosus has shorter muscle fibers than the semitendinosus and biceps femoris (Kellis et al., 2012, Ward et al., 2009). It is rational to think that the shorter the muscle fibers are, the more elongated the tendon of the muscle will be when the muscle–tendon unit is elongated. Moreover, the shear elastic modulus of the tendon is higher than that of the muscle (Kot et al., 2012). Therefore, more tension is required to elongate the tendon, and the semimembranosus, which has the shortest muscle fiber length among the hamstring muscles, therefore has the highest tension among them. However, to the best of our knowledge, no study has investigated the relationship between the shear elastic modulus and the changes in muscle fiber and tendon length; therefore, this aspect requires further research.

Comparison among the three pelvic positions

We examined whether an anterior or posterior tilt of the pelvis could change the passive tension applied to the hamstring muscles at the same hip joint angle (T–F angle). In this study, there was no difference in the T–F angle, but the P–F angle in Anterior Tilt was significantly larger than that in Non-Tilt or Posterior Tilt, and the P–F angle in Non-Tilt was significantly larger than that in Posterior Tilt. Thus, this study revealed that, at the same hip joint angle, the passive tension applied to the hamstring muscles varies depending on the pelvic tilt. The shear elastic moduli of the semitendinosus, semimembranosus, and biceps femoris increased significantly with an anterior tilt of the pelvis, with the exception of the difference in the semitendinosus between Anterior Tilt and Non-Tilt, and that in the biceps femoris between Non-Tilt and Posterior Tilt. This result suggests that an anterior tilt of the pelvis increases the passive tension applied to the hamstring muscles. Moreover, the passive knee flexion torque and P–F angle increased significantly with an anterior tilt of the pelvis without an increase in the T–F angle. Considering these results, the reason for the increase in the passive tension applied to the hamstring muscles with an anterior tilt of the pelvis is thought to be that the practical hip flexion angle (P–F angle) increases with an anterior tilt of the pelvis, although the apparent hip flexion angle (T–F angle) remains almost the same. Therefore, when trainers and therapists advise athletes about the best sprint position to prevent hamstring muscle strain, it is important to focus not on the angle of the femur with respect to the trunk or on the anterior tilt of the trunk but on the anterior tilt of the pelvis.

Limitations of this study

Hamstring muscle strain most commonly occurs during the terminal swing phase of sprinting, not only because of passive elongation but also as a result of the high intensity of the contraction (Thelen and Chumanov, 2005, Yu and Queen, 2008) that occurs during this phase. However, in this study, we investigated the shear elastic modulus only during passive elongation without contraction. Therefore, further research is required to clarify the differences in tension applied to the semitendinosus, semimembranosus, and particularly the biceps femoris during contraction to reveal the factors inducing hamstring muscle strain during the terminal swing phase of sprinting. In addition, previous studies have reported that failure by passive tension occurs at either end of the musculotendinous junction of the muscle (Garrett et al., 1988) and that hamstring muscle strain occurs at the musculotendinous junction (De Smet and Best, 2000). We measured the shear elastic modulus only at the belly of each muscle. As the musculotendinous units might not be a mechanically homogeneous complex, further research is required to clarify the effects of passive elongation and pelvic tilt on the passive tension applied to the musculotendinous junctions of the semitendinosus, semimembranosus, and biceps femoris. Moreover, although contraction of the quadriceps muscle might affect our results, we did not monitor this. Therefore, in future studies, quadriceps muscle contraction should be monitored using electromyography.

Conclusion

Our results suggest that the passive tension applied to the semimembranosus is higher than that applied to the semitendinosus and biceps femoris when the hamstring muscles are passively elongated, and that the passive tension applied to the hamstring muscles increases under an anterior tilt of the pelvis.

Conflicts of interest

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Table 1. Joint angle (degrees) of T–F and P–F at three pelvic positions

	T–F	P–F
Anterior Tilt	70.4 ± 3.8	73.6±6.1 Ⅰ, Ⅱ
Non-Tilt	70.4 ± 2.7	66.6±6.8 Ⅰ
Posterior Tilt	70.1 ± 4.2	58.6±5.6

Values are expressed as mean ± SD (standard deviation).

Abbreviations:

T–F: the angle of femur axis to trunk axis;

P–F: the angle of femur axis to the perpendicular line to pelvis axis;

Significantly higher than Posterior Tilt: Ⅰ ($p < 0.01$);

Significantly higher than Non-Tilt: Ⅱ ($p < 0.01$).

Table 2. Shear elastic modulus (kPa) of semitendinosus, semimembranosus, and biceps femoris at three pelvic positions

	semitendinosus	semimembranosus	biceps femoris
Anterior Tilt	39.2±10.3 [Ⅰ]	78.0±16.5 [A,B, Ⅰ, Ⅱ]	58.9±21.9 [a, Ⅰ, ii]
Non-Tilt	34.1±6.7 [i]	57.9±14.6 [A,B, i]	40.3±17.7
Posterior Tilt	25.5±4.6	44.0±11.5 [A,B]	31.3±15.6

Values are expressed as mean ± SD (standard deviation).

Comparison among muscles:

Significantly higher than semitendinosus: A ($p < 0.01$), a ($p < 0.05$),

Significantly higher than biceps femoris: B ($p < 0.01$)

Comparison among pelvic positions:

Significantly higher than Posterior Tilt: Ⅰ ($p < 0.01$), i ($p < 0.05$)

Significantly higher than Non-Tilt: Ⅱ ($p < 0.01$), ii ($p < 0.05$)

Table 3. Passive knee flexion torque (Nm) at three pelvic positions.

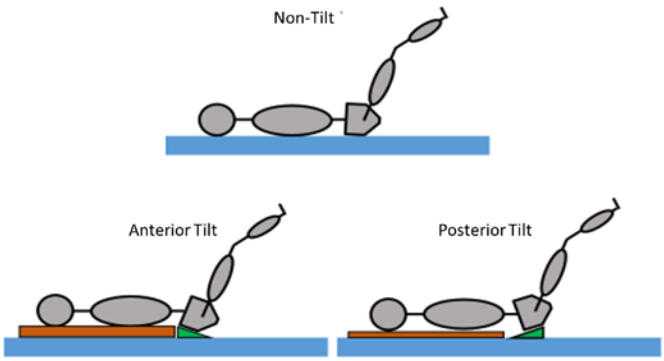
Anterior Tilt	9.8±3.0 [I, ii]
Non-Tilt	8.0 ± 2.4 [I]
Posterior Tilt	5.4 ± 1.6

Values are expressed as mean ± SD (standard deviation).

Significantly higher than Posterior Tilt: I ($p < 0.01$).

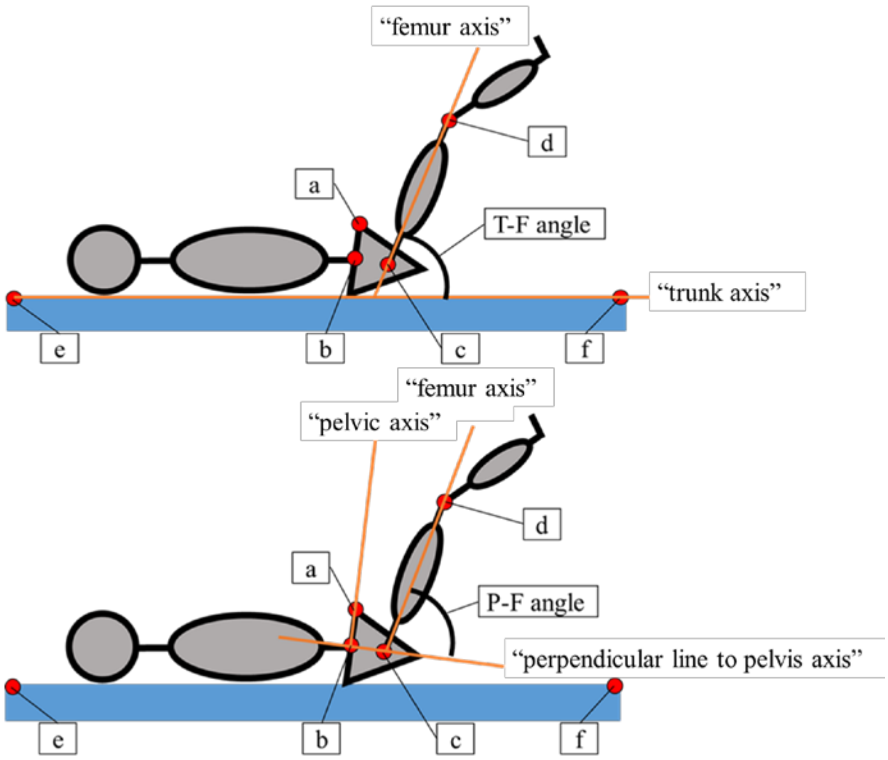
Significantly higher than Non-Tilt: ii ($p < 0.05$).

Figure 1. Schematic representation of the experimental setup



In pelvic alignment, the neutral pelvic position was defined as “Non-Tilt,” and anterior and posterior tilt positions of the pelvis with respect to Non-Tilt were defined as “Anterior Tilt” and “Posterior Tilt,” respectively.

Figure 2. Schematic representation of joint angle measurement



Red dots (a)–(f) indicate reflective markers. The line that links the markers at (e) and (f) was defined as the trunk axis; the line linking the markers at (a) and (b) was defined as the pelvic axis, and that linking the markers at (c) and (d) was defined as the femur axis. The pelvis–femur angle (P–F angle) was defined as the angle of the femur axis with respect to a line perpendicular to the pelvic axis, and the trunk–femur angle (T–F angle) was defined as the angle of the femur axis with respect to the trunk axis.

Figure 3 Representative ultrasound shear wave elastographic images of each muscle