Ultrasonographic Measurement of Tendon Displacement Caused by Active Force Generation in the Psoas Major Muscle

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Abstract: The purpose of this study was to examine the validity of using ultrasonography for detecting the force generated by the psoas major muscle, a muscle positioned in the deep trunk. We measured the displacement of central tendon on B-mode ultrasound images of two different longitudinal sections of the muscle during passive hip flexion-extension and isometric hip flexion at varied hip angles. In both tasks, the values of tendon displacement obtained independently from each section coincided well, indicating that tendon displacement took place along a straight trajectory, i.e., close to the nodal line between two scanned planes. It was strongly correlated with both the hip angle ($R^2 = 0.98$) and the hip-flexion torque ($R^2 = 0.83$). In the second set of experiment, we measured the tendon displacement during dynamic movements with the combination of ultrasonography and VICON-based motion analysis. From the tendon displacement during dynamic thigh lifting and walking, the force generated by the muscle could be estimated by extracting the force-related component. These results indicate that ultrasonography of the psoas major muscle can measure the displacement of its central tendon accompanied with either length change of the muscle or the elongation of tendon. Although much attention has to be paid to the limitations of this methodology, ultrasonography may be useful for detecting the force generation of the muscle during a variety of dynamic movements.

Key words: ultrasonography, psoas major muscle, tendon displacement, tendon elongation.

Muscles in the deep region of trunk, e.g., the psoas major muscle, are considered to play important roles in a variety of exercises and movements by stabilizing the torso and lumbar spine [1–4]. However, fewer studies have been conducted on these muscles than on muscles positioned near the surface of the body, due probably to their inaccessibility. Invasive methods such as an insertion of wire electrodes [1, 2, 4] are usually required to examine the functions of these muscles.

There are some alternative, non-invasive methods to examine their functions, including T2-weighted magnetic resonance imaging [5] and $^{18}$F-fluorodeoxyglucose positron emission tomography [6]. However, most of these alternative methods have some considerable problems, especially in time resolution. Among these alternatives, ultrasonography has relatively high time resolution. It has been successfully used to investigate the architectural changes of muscle-tendon units during contraction, e.g., muscle thickness, fascicle length, pennation angle, and displacement of aponeurosis and tendon [7–12]. Some of these architectural changes reflect muscle contraction [10], so that ultrasonography has been expected to be used for detecting the active force generation of muscle. Several studies have already used this method for some deep trunk muscles [10, 12, 13]. However, the muscles studied so far were those positioned not in the deepest region of the trunk (less than 50 mm from the body surface). Moreover, most of these studies have shown the forces during isometric contraction only. So to learn more about the roles played by deep trunk muscles, finer analyses for dynamic, non-isometric contractions are to be made.

For examining the force in dynamic contractions with ultrasonography, some essential requirements have to be satisfied. First, the selected architectural measure must be consistently obtained and unaffected by incidental factors, such as changes in scanned plane. Second, the architectural change of muscle due exclusively to its active force generation must be separated from that simply caused by its geometric deformation, e.g., length change of the
whole muscle-tendon unit. Third, a selected architectural measure must have a well-defined relation to the active force of muscle. The present study aimed to examine whether these requirements are satisfied for a representative deep-trunk muscle, the psoas major muscle, which has been regarded as important not only in trunk stabilization, but also in generating dynamic movements such as walking and running [14]. The displacement of the central tendon was chosen as a measure of active force of the muscle.

METHODS

The current study consisted of two sets of experiments. The first aimed to examine whether the three essential requirements are satisfied. The second investigated whether the active force generation of the muscle can be successfully detected during several fundamental dynamic movements.

Subjects. Ten healthy males (age, 21.1 ± 1.5 years; height, 172.5 ± 4.6 cm; body mass, 66.2 ± 4.5 kg, mean ± SD) and 2 healthy males (age, 26.0 ± 4.0 years; height, 177.8 ± 2.8 cm; body mass, 71.3 ± 5.3 kg, mean ± SD) participated in the first and second experiments, respectively. The experimental procedure was approved by the ethical committee of the Japan Institute of Sports Sciences, and all subjects gave their informed consent before the experiment.

Experimental procedures. In the first experiment, to examine the two factors, i.e., length change of the muscle-tendon unit and change in force generated by the muscle, two experimental protocols were independently used: passive hip flexion and extension, and isometric hip flexion at fixed hip-joint angles. Each subject lay prone on a bed, and the arm of an isokinetic dynamometer (CON-TREX MJ, CMV AG, Zurich/Switzerland) was firmly attached to the right hip joint (Fig. 1a). The subject then performed a passive trial first: he was instructed to relax all his muscles around the right leg, and his right hip joint was flexed and extended passively by the dynamometer, repeatedly 2 times. The range of hip-joint movement was set from 0º to 100º (0º at full extended position). The angular velocity of the movement was set at 30º/s. After the passive trial, each subject performed an active isometric trial: the subject was instructed to exert isometric hip-flexion torque gradually from a fully relaxed level to a maximal level, repeatedly 2 times. The range of hip-joint movement was set from 0º to 100º (0º at full extended position). The angular velocity of the movement was set at 30º/s. After the passive trial, each subject performed an active isometric trial: the subject was instructed to exert isometric hip-flexion torque gradually from a fully relaxed level to a maximal level, repeatedly 2 times. The angle of hip joint was set at 30º, 50º, 70º, and 90º. The subjects were also instructed not to move the upper body during the tasks, so as to avoid the lateral and dorsal-ventral movements of the lumbar spine, which might be related to the function of the psoas major muscle.

In the second experiment, each subject also performed passive and isometric trials by use of an isokinetic dynamometer (Biodex, Biodex Medical Systems, USA) before performing dynamic movements. In a standing position with the left foot, the right hip joint was flexed and extended passively, repeatedly 3 times, from 0º to 90º (0º at
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upright standing position) with the angular velocity at 30°/s. Afterward, the subjects exerted isometric hip-flexion torque gradually from a fully relaxed level to a maximal level, then returned again to the relaxed level, at the hip-joint angle of 60°.

After the passive and isometric trials, each subject performed two dynamic trials, including a thigh-lifting trial and a walking trial (Fig. 1b). In the thigh-lifting trial, the subject lifted his right and left thighs alternately and repeatedly to the height where the thigh was approximately horizontal. The thigh lifting was performed at a constant rhythm (60 beats/min) by the aid of metronome. In the walking trial, the subject walked on the laboratory floor with his natural cadence and stride. Three cycles of thigh lifting and three stride-cycles of walking were used for analysis.

Ultrasoundography. In the first experiment, two independent sections of the muscle were scanned simultaneously using two ultrasound apparatuses (B-mode, SSD-6500, and SSD-900, ALOKA, Japan) equipped with electronic linear array probes of the same specification (3.5-MHz wave frequency, ALOKA, Japan). Two probes were fixed longitudinally on different positions of the surface of right lower back with double-sided adhesive tape. Viewing the scanned images, their positions were finely adjusted and fixed firmly with towels and elastic bands so as to obtain clear images of the central tendon (Fig. 1c). The images obtained by each ultrasound apparatus were separately recorded on digital-video tapes at 30 Hz, then transferred to a personal computer for further analysis. Two separately recorded images were synchronized with reference to a time mark recorded on each image simultaneously. The images were also synchronized with outputs from the dynamometer with reference to the torque signal, which was also recorded and cognizable on one ultrasound image.

In the second experiment, only one ultrasound apparatus (SSD-6500) was used with the same-type probe used in the first experiment. The probe was fixed on the right lower back where a clear image of the central tendon could be obtained. It was fixed with double-sided adhesive tape and positioned with a splint made of fiberglass and water-activated synthetic resin (Light Splint II, Alcare Co. Ltd., Japan), towels, and elastic bands. The image obtained was recorded on a digital-video tape at 30 Hz, then transferred to a personal computer for further analysis.

Hip-joint kinematics. In the second experiment, the hip-joint angle on a sagittal plane was collected using a motion analysis system (120 Hz, VICON, Vicon Motion Systems Ltd., UK) and reflective markers positioned over landmarks of the pelvis and right leg. Details of the marker position and calculation of the joint angle were determined manually according to the instruction of VICON gait analysis model (Plug-in Gait).

The motion analysis system also collected and recorded the ultrasound image simultaneously during all the trials, though the quality of recorded image was inferior to that recorded on the digital-video tape. With reference to the image recorded in the motion analysis system, the synchronization of the kinematics data with the ultrasound image recorded on the digital-video tape was obtained.

Measurement of tendon displacement. Using digitizing software (NIH image, National Institute of Health, USA), the position of proximal end of the central tendon (point P, Fig. 2) was digitized on each image. In the first experiment, the displacement of P (ΔP) was determined as the distance between P and P0 (the position of P when the hip joint was at 0° in the passive trial, or when the hip-joint torque was 0 Nm in the active isometric trial). For evaluating the reproducibility of the digitizing process, we measured ΔP three times on the same image for all trials by all subjects, and calculated standard deviations (SD). A mean value of ΔP from these repeated measurements was used for further analysis. To individuate the values of ΔP obtained from two different sections, the one obtained from the section oriented from dorsal to ventral was represented as ΔPp, whereas the other, from the section oriented from lateral to medial, was represented as ΔPm (Fig. 1c).

In the second experiment, the displacement of tendon was determined from positions of the edge of central tendon and the iliopectine eminence, which is a "via point" of the tendon on the pelvis [15] (Fig. 3a). The 3-dimensional global coordinate of tendon edge was obtained from a combination of VICON-based probe kinematics and the position of tendon edge visualized on the ultrasound image. Since the ultrasound probe was not entirely visible because of the fixation materials, i.e., the splint and towels, its position was calculated with subsidiary reference to the splint position, which was firmly fixed on the probe and would show the same kinematics with it. One marker attached to the probe directly and two markers attached to the lower edges of the splint were used for calculating the positions of probe and ultrasound-scanning plane (Fig. 3b). Thereafter, the global coordinate of tendon edge visualized on the ultrasound image was determined. On the other hand, the coordinate of iliopectine eminence was obtained from VICON-based pelvic kinematics with the assumption of pelvic morphology based on anatomical literature [15]. The location of iliopectine eminence was defined on the local orthogonal pelvic coordinate, with the origin positioned on the mid-point of the right and left anterior superior iliac spines (ASISs) and three orthogonal coordinate axes, i.e., medio-lateral axis toward the ASIS position from the origin, antero-posterior axis toward the mid-point of the right and left posterior superior iliac spine (PSISs) from the origin, and the crano-caudal axis downward vertically (Fig. 3c). The position of iliopectine eminence was assumed to be 30.2% of the inter-ASIS distance lateral along the medio-lateral axis, 9.5% of the distance between the mid-ASIS and mid-PSIS backward along the antero-posterior axis, and 21.5% of the inter-
ASIS distance downward along the cranio-caudal axis from the origin. Then the change of distance between the tendon edge and the iliopubic eminence was determined as ΔP (0 mm at the time when the hip joint was at 0° in the passive trial). This procedure made it possible to measure the tendon displacement relative to the pelvis, irrespective of unexpected movement of the probe due to some trunk movement or inertial force.

Fig. 2. Typical ultrasound images of the psoas major muscle during passive trial (a), active isometric trial (b), and dynamic thigh lifting (c). The inset indicates hip-joint angle (a–c) and hip-flexion torque (a, b). The proximal end of the central tendon (arrows) was determined as point P. All trials caused the longitudinal movement of P toward the proximal direction (right to left). (d) Schematic diagram of ultrasound image, showing the positions of psoas major muscle and its central tendon.
Data analysis. For comparison between $\Delta P_a$ and $\Delta P_b$ measured in the first experiment, a simple linear regression analysis was performed, and their difference was examined with residual standard deviation (RSD) from an ideal first-order regression line. The RSD was then compared with the SD for digitizing reproducibility.

For estimation of the effects of length change and force generation on the tendon displacement, a simple linear regression analysis was performed between $\Delta P_a$ and hip angle, while a quadratic regression analysis was performed between $\Delta P_a$ and hip-flexion torque. The coefficient of determination ($R^2$) was then calculated in each analysis. Although hip-flexion torque would not completely correspond with force generated by the muscle, we used it as an indicator of force generation of the muscle.

For detecting the force generation during isometric hip flexion, thigh lifting, and walking in the second experiment, the tendon displacement during these exercises was compared with that during the passive hip movement. A linear function between $\Delta P$ and hip-joint angle during passive hip flexion-extension movement was determined with least-squares regression. Using this equation, the component of tendon displacement, which was supposed to be related to the active force generation ($\Delta P_{\text{active}}$) rather than the change in hip-joint angle, was estimated by subtracting the predicted passive component from measured $\Delta P$. The estimated $\Delta P_{\text{active}}$ during isometric hip flexion was plotted against the hip-flexion torque, and a quadratic regression analysis was performed between them. $\Delta P_{\text{active}}$ obtained during dynamic movements was averaged over three thigh-lifting cycles or three stride cycles of walking, defined from a right foot contact to the next, within each subject, and thereafter averaged for all subjects.

RESULTS

In the first experiment, $P_0$ could not be determined in some subjects in the passive trial, because point P was out of the ultrasound image when their hip joint was fully extended. In such cases, $P_0$ was determined as the position of P just before P went out of the image. Consequently, the range of hip joint, from which both $\Delta P_a$ and $\Delta P_b$ successfully obtained, was from 34.5° ± 17.6° (mean ± SD) to 100° (fixed terminal position). In some active isometric trials, $P$ was also out of the ultrasound image when the hip-flexion torque was zero. Furthermore, we sometimes failed to obtain the ultrasound image of central tendon reproducibly in the lateral-medial muscle section in some

Fig. 3. (a) Schematic diagram showing the positions of the central tendon of psoas major muscle and the "via point" of the tendon on the iliopectineal eminence. Determinations of point P (on ultrasound image) and positions of the probe and "via point" could eliminate the effects of unexpected movement of the probe during the tasks. (b) Schematic diagram showing the marker setup for defining the probe position, and moreover for defining the position of the ultrasound image obtained. With a determination of point P (i.e., the edge of central tendon) on the ultrasound image, its global coordinate was calculated. (c) Schematic diagram showing the marker setup for defining the pelvis. On the local coordinate of pelvis defined by four markers, the position of "via point" (i.e., the iliopectineal eminence) was defined, with reference to anatomical literature [15].
and active isometric trials (Fig. 4). The mean ΔPb was 1.17 mm when averaged for all trials. When this was divided by the maximum value of ΔPb in each trial, it gave a mean CV of 5.7%. This level of CV was similar to those previously reported in ultrasonographic measurements with muscles near the surface of body [7–9]. No consistent effect of hip-joint angle. In the second experiment, P was identified on the ultrasound image throughout all trials in all subjects. ΔP was again highly correlated with the hip-joint angle (Fig. 5a, $R^2 = 0.94$, mean for all subjects) in the passive trial, and also with the hip-flexion torque (Fig. 5b, $R^2 = 0.88$, mean for all subjects) in the isometric trial. In the thigh-lifting and walking trials, P moved in response to hip flexion-extension movement, though its behavior was slightly different between the trials. Figure 5a shows the relations between ΔP and hip angle during thigh lifting and during walking. In some phases during both thigh lifting and walking, P moved proximally more than predicted from the regressions for the passive hip movement. The correlation of ΔPb with hip-flexion torque tended to be weaker than that with hip-joint angle. At four different hip angles, the ΔPb-torque relations in isometric contraction appeared to show slightly different configurations. However, no consistent effect of hip-joint angle was seen throughout subjects.

In the first experiment, ΔP was strongly correlated with either hip angle or hip-flexion torque. The mean values of $R^2$ were 0.98 and 0.83 for the passive and active isometric trials, respectively. The correlation of ΔPb with hip-flexion torque tended to be weaker than that with hip-joint angle.

Subjects, because change in the surface shape of trunk caused a slight shift of the probe orientation, and the central tendon often disappeared from the ultrasound image. Consequently, the number of subjects from which both ΔPb and ΔPa successfully obtained in the active isometric trial were 7, 6, 5, and 4 at hip-joint angles of 90°, 70°, 50°, and 30°, respectively. No visible movement of the lumbar spine was found to occur in both the passive and active isometric trials.

P moved proximally during hip flexion and distally during hip extension in the passive trial (Fig. 2a), and it also moved proximally as the hip-flexion torque increased and distally as the torque decreased in the active isometric trial (Fig. 2b). The SD of repeated digitizing procedure was 1.17 mm when averaged for all trials. When this was converted to the coefficient of variation (CV) by dividing SD by the maximum value of ΔP in each trial, it gave a mean CV of 5.7%. This level of CV was similar to those previously reported in ultrasonographic measurements with muscles near the surface of body [7–9]. No considerable difference in either SD or CV was observed between ΔPa and ΔPb in either passive or active isometric trials.

Figures 4a and 4b show typical relations between ΔPa and ΔPb. The mean RSD was 0.71 mm, which was smaller than the SD of digitizing procedure. This indicates that the difference between ΔPb and ΔPa is ignorable when considering the digitizing error. Figures 4c and 4d show typical relations between ΔPa and hip angle in the passive trial, and between ΔPa and hip-flexion torque in the active isometric trial at varied hip-joint angles, respectively. In these relations, ΔPa was strongly correlated with either hip angle or hip-flexion torque. The mean values of $R^2$ were 0.98 and 0.83 for the passive and active isometric trials, respectively. The correlation of ΔPb with hip-flexion torque tended to be weaker than that with hip-joint angle. At four different hip angles, the ΔPb-torque relations in isometric contraction appeared to show slightly different configurations. However, no consistent effect of hip-joint angle was seen throughout subjects.

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DISCUSSION

The present study showed that ultrasonography can be used to measure the displacement of central tendon in the psoas major muscle, caused by both length change of the muscle-tendon complex and the active force generated by the muscle. The results also suggest that the present methodology is a powerful, non-invasive tool for detecting force generation of the muscle during a variety of dynamic movements. As mentioned in the introduction, at least three fundamental requirements may have to be satisfied for this. The results indicate that these requirements were mostly satisfied, though some minor problems were also found concurrently.

**Consistency of architectural measure**

To answer the first requirement, ultrasound images were taken from two separate sections independently in the first experiment. One factor, which makes the structural analysis difficult, is the complicated architecture of trunk muscle. For the psoas major muscle, its unique, me-
dially twisted structure of muscle belly [16] might cause three-dimensional movements of the central tendon. However, the present results show that tendon displacement took place on a straight trajectory in each scanned image, suggesting that the tendon moves along a nodal line between two scanned sections. Accordingly, similar values of ΔP were obtained from two sections (Fig. 4, a–b). These results suggest that a proper value for tendon displacement can be obtained from either section. Consistency of architectural measure

Besides the architectural features of muscle, the probe displacement should affect the result of ultrasonographic measurement. We sometimes failed to obtain the ultrasound image of central tendon in the lateral-medial muscle section during the active isometric trial because of a subtle change in the surface shape of the side trunk, which probably resulted from respiration and contractions of abdominal muscles. On the other hand, we successfully obtained consistent images of the tendon in the dorsal-ventral muscle section. The less-changeable surface shape of the lower back may enable this.

Another problem of probe displacement should be its effect on tendon-displacement measurement. The probe displacement might possibly induce the “apparent” tendon displacement on the scanned ultrasound image even if the tendon does not move. In the second experiment, trunk movements and/or inertial forces accompanied with dynamic movements were expected to cause probe displacement. Thus the position of ultrasound probe was monitored by the motion analysis system to compensate for the displacement.

**Estimation of tendon elongation**

The present study separately investigated two components involved in tendon displacement: geometrical displacement due to length change of the muscle, and structural deformation, i.e., elongation by the active force generation. The second among these requirements would be satisfied if tendon displacement caused by these two components was separated successfully during dynamic movement. For passive hip flexion and extension, the tendon displacement showed a well-defined linear relation to the hip-joint angle, indicating that the position of central tendon directly reflects the length of the muscle when the muscle is fully relaxed. The ratio of tendon displacement to the change in joint angle corresponds to the moment arm length [17], and that of the psoas major muscle was determined as 28.4 mm (mean for all subjects) in the present study, which was consistent with previous reports with cadavers [18].

During isometric contractions in both the first and second experiments, the tendon position also moved in the proximal direction. If the length of whole muscle-tendon complex is unchanged, this tendon displacement would reflect the elongation of the central tendon caused by the active force generation of the psoas major muscle. When length change and active force generation take place simultaneously as in the second experiment, this force-related component may readily be separated from the length-related component because the latter component can be determined with reference to the relation between the tendon displacement and the hip-joint angle.

**Detection of force generation via tendon elongation**

The third requirement would be satisfied if the force-related component of ΔP would be well correlated with the active force. Because not all the architectural measures have a well-defined correlation with force or activation level of muscle [10], it is crucial for detecting active force to choose what measures to be used. In this study, tendon displacement, which includes tendon elongation when stretched, was chosen as the architectural measure because tendon is well known to have a quasi-elastic property, and its elongation generally shows a non-linear relation to the force applied [19]. As expected, a strong correlation was seen between ΔP and isometric torque, though it should be noted that the isometric torque would not uniquely represent the force generated by the psoas major muscle; instead, it would represent the sum of the forces generated by several synergistic muscles. From the viewpoint of the architectural features of three major hip flexors, i.e., the psoas major muscle, the iliacus muscle, and the rectus femoris muscle (the cross-sectional area, 19.5, 27.2, and 28.9 cm² [15]; the pennation angle, 13.4, 26.5, and 22.0° [15]; the moment arm length, 30, 30, and 22 mm [20], respectively, at the hip-joint angle of 60°), the contribution of the psoas major muscle on torque exertion is expected to be at most 30%. It is unknown whether relative contributions of these muscles change with either the hip-flexion torque or the hip-joint angle. However, an electromyographic study has shown that the activity of psoas major muscle increases with the hip-flexion effort [1]. This is consistent with the present ΔP-torque relations (Figs. 4d and 5b), and suggests that ΔP can be a measure either of activation level or of contractile force of the psoas major muscle, when expressed relative to maximum voluntary contraction.

In the first experiment, the correlation of ΔP with hip-flexion torque in the active isometric trial tended to be weaker than that with hip angle in the passive trial (Fig. 4). Furthermore, the ΔP-torque relation exhibited slightly different configurations among four different hip-angle conditions. There may be several possible reasons for this. First, as described above, hip-flexion torque does not represent only the force generated by the psoas major muscle, and the relative contributions of synergists may change slightly with the hip-joint angle and/or torque. Second, the viscosity of tendon caused the different ΔP-torque relation.
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between the ascending and descending phase in torque exertion, i.e., hysteresis [21, 22]. Third, the central tendon might have already been stretched slightly by passive tension at the hip-extended position. Fourth, slight probe displacement might occur during torque exertion. And fifth, the subtle change in hip angle as a result of insufficient hip-joint fixation might occur. The change in hip-joint angle may have a considerable effect because the tendon displacement related to length change of the muscle-tendon complex would occur easily with it (2.02° change in hip-joint angle would cause 1 mm tendon displacement, a mean for all subjects). When the probe position and hip-joint angle were measured kinematically in the second experiment, the regression analysis between ΔP (ΔP_{active}) and torque gave much higher R².

In the second experiment, ΔP_{active} increased consistently during both thigh lifting and walking. During thigh lifting, the increase of ΔP_{active} occurred along with hip flexion, indicating that the psoas major muscle generated active force to keep the thigh lifted. During walking, the increase of ΔP_{active} occurred between the mid-stand and the onset of hip flexion. This is consistent with previous electromyographic studies [14]. Interestingly, two subjects showed different patterns in ΔP_{active} during walking (Fig. 5a), which might be due to either the difference in visco-elastic properties of tendon [23–25] or the difference in muscle-recruitment strategy for walking between individuals. At present, no conclusion can be drawn, because precise determination of the visco-elastic properties of tendon could not be made for each individual. However, the present methodology would be useful at least for investigating the task-related activities of the psoas major muscle within individuals.

**Limitations and potentials of ultrasonography in detection of force generation**

There are several limitations to consider in the present methodology. First, the resolution of ultrasound image of the deep trunk is inferior to that of near the surface of body, a result of the low-frequency characteristic of ultrasound probe suitable for scanning the deep region. Ultrasoundography used with a high-frequency probe can provide the image with high resolution, but cannot be used to examine deeper regions of the body because of the high level of filtering of the sound waves. The resulting low resolution might make it difficult for a less-experienced examiner to determine the proximal end of tendon. Second, active force generation cannot be detected directly from the tendon position, but it can be detected from its change from the resting position. As with some subjects in the first experiment, this might limit the range of motion to be examined because of the limited field of view of ultrasound probe. Third, the present procedure for tendon-displacement measurement with reference to the assumed position of ilipubic eminence might cause substantial errors in some postural conditions, e.g., deeply flexed hip joint and/or flexed trunk, which might possibly change the via point of central tendon. Thus the present methodology may have to be limited to movements without such postural conditions. Fourth, the viscosity of tendon may affect its strain rate, especially at ballistic force generation. This would cause the difference in phase between force and strain.

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