Abstract  Deep squatting places a burden on the lower limb muscles and influences postural balance. We attempted to determine the effects of postural changes on the rectus femoris, tibialis anterior, gastrocnemius, soleus, and extensor digitorum brevis muscles during squatting in 8 healthy male subjects. Three squatting conditions were involved: full squatting (FS), tiptoe squatting (TT), and tiptoe squatting on a 15° slope (TTS), performed randomly and recorded in a period of 4 min for each task. The influence of the squatting condition on electromyography and vertical ground reaction force parameters was examined in order to observe the effect of postural alteration on muscle activity and balance control. The results showed that the change of squatting posture from FS to TT decreased the activity of the rectus femoris and tibialis anterior muscles. FS has been suspected as a main cause of musculoskeletal complaint during prolonged squatting. In contrast, as the heel was lifted, the extensor digitorum brevis muscle increased to 39% of maximum activation. On the other hand, sway analysis at TT showed balance instability regarding the large area occupation of the center of pressure displacement. The presence of a 15° slope significantly reduced the muscular load. This simple study suggests that the inclusion of a sloping surface in daily activities that requires a squatting posture would be an effective means to reduce muscular load.

Keywords: squatting strategy, foot slope, tiptoe, sway analysis

Introduction

Among most people living in Asia and Africa, the ability to adopt a squatting posture is considered the mark of an adaptable personality. It has become generally known that culture shapes the way of human activity by teaching this kind of posture as well as kneeling or sitting cross-legged (Demura and Uchiyama, 2005). In Western countries, adults are not generally accustomed to the deep squatting posture and find it uncomfortable when they have to squat with full flexion of the knee. However, the effects of this posture may cause an increased risk of musculoskeletal stress or injury for those who often work close to ground level (Dyrby et al., 1997; Kaneda et al., 2001). Regarding floor activity, people adopt a squatting posture for the sake of convenience, but this posture sometimes becomes harmful and may lead to irreparable damage to some part of the body. Since the full squat entails a loose balance, the obese require relatively more room between the abdomen and the thigh (Sriwarno et al., 2006). It is assumed that the limitation of ankle flexion provides balance control. One of the strategies to maintain balance without sacrificing the ability to work close to the ground is to increase the hip joint angle, therefore providing enough abdominal room. As a counterbalance, the heel is lifted, which shifts the head of the metatarsophalangeal to the point of rotation and therefore places the thigh almost parallel to the floor. This is known as the “tiptoe” posture which is performed by shifting the body weight to the head of the metatarsophalangeal joint (Muray et al., 1967; Saito et al., 2007).

Maintaining body balance is important in relation to the muscular tension necessary to hold the center of pressure within the support area while squatting. There may be many reasons for adopting the tiptoe squatting posture, but few studies have investigated the relation between deep squatting and the burden it places on lower limb muscles and balance stability. One assumption is that the tiptoe posture in deep squatting may result in less activity of certain lower extremity muscles during heel supination (Shimizu and Andrew, 1999; Tansey and Briggs, 2001).

Based on reports that a proper squatting posture is characterized by minimal muscle effort and balance
consistency provided by appropriate support, the present investigation examines the conditions necessary for balance maintenance and stability in a squatting position. Although the foot slope has been discussed in previous studies concerning foot plantarflexion (Nordin and Frankel, 2001; Tansey and Briggs, 2001), in the present study we applied a 15° slope for the feet in light of the burden of the lower limb muscles during squatting. Since daily activities often involve deep squatting, it is important to understand how posture muscles are controlled in maintaining balance stability. The aim of this study is to determine the role of the lower limbs muscles in maintaining squatting balance in both the ankle and the tiptoe strategies as well as proposing a way of reducing the muscular load by presenting the use of the foot slope. Furthermore, the application of the proposed method may assist in a more appropriate assessment of such areas as occupational safety and health or in balance exercises to improve working efficiency.

Methods

First, anthropometric measurements were performed to gather information regarding physical characteristics for each subject (Table 1). A total of 8 Indonesian male subjects were employed, none of which had experienced musculoskeletal disease for at least one year before the day of the experiment. The subjects were required to have experience in working in the full squat position in daily life. All subjects showed the ability of deep squatting without any difficulties during familiarization of task. The subjects were also asked not to consume alcohol or medications that would reduce consciousness prior to the sway trajectory measurement. Informed consent was obtained from each subject following orientation and an explanation of the experiment’s protocol.

The subjects were asked to perform full squat postures in two ways: squatting with the ankle joint as the center of rotation (ankle strategy) and squatting with the head of the metatarsophalangeal joint as the center of rotation (tiptoe strategy) with their eyes open and with bare feet. Footprints were projected vertically over a sheet of paper to determine the base of support (BOS) and the angle between the feet (FA) (Fig. 1D) for each squatting posture. During the holding task, the subjects were instructed to squat as quietly as possible; therefore, the effect of falling backward could be minimized regarding the distribution of the center of pressure (COP) from the vertical ground reaction force (GRF) platform. The upper limbs or the hands had to be held over the thigh while the knee joint angle was in the necessary full flex position. The subjects had to squat for 4 min during recording and were allowed to rest in a comfortable chair for 3 min after each trial. The squatting strategy in these experiments involved three tasks: the ankle strategy (FS), the tiptoe strategy (TT), and the tiptoe on a 15° foot slope strategy (TTS) randomly as shown in Fig. 1A–C.

The five markers were positioned on the subject’s body to determine the body’s segmental joints. These included the

| Table 1 Mean and standard deviation of general characteristics of subjects |
|----------------|----------------|----------------|----------------|----------------|
|                | Age (years) | Height (cm) | Weight (kg) | BMI (kg/cm²) | Body type     |
| Subject 1     | 36.0        | 170.0       | 83.5        | 28.9          | Over-weight   |
| Subject 2     | 30.0        | 170.5       | 93.5        | 32.2          | Obese         |
| Subject 3     | 35.0        | 161.4       | 64.5        | 24.8          | Normal weight |
| Subject 4     | 38.0        | 169.6       | 76.0        | 26.4          | Over-weight   |
| Subject 5     | 33.0        | 170.2       | 77.5        | 26.8          | Over-weight   |
| Subject 6     | 33.0        | 164.8       | 53.4        | 19.7          | Normal weight |
| Subject 7     | 28.0        | 172.0       | 57.7        | 19.5          | Normal weight |
| Subject 8     | 27.0        | 166.0       | 50.3        | 18.3          | Normal weight |
| Average       | 32.5        | 168.1       | 69.6        | 24.6          |               |
| SD            | 3.6         | 3.4         | 14.5        | 4.7           |               |

1. BMI: Body Mass Index
2. SD: Standard Deviation
3. Body type is defined by following the classification of BMI standard (18.0–24.9: normal weight, 25.0–29.9: over-weight, and over 30: obese).

Fig. 1 Three tasks performed by the subjects: full squatting/FS (A), tiptoe squatting/TT (B), and tiptoe squatting on a 15° slope/TTS with the presence of a tiptoe stopper (C). Markers were attached to the subjects’ body for body joint determination: hip (A’), ankle (B’), and head of the metatarsophalangeal joint (C’). The foot projection measurement with respect to the forefoot placement characteristics with operational definitions (D): base of support (BOS) and feet angle (FA).
acromion, the great trochanter, the lateral epicondylus, the lateral malleolus, and the fifth head of the metatarsophalangeal joint. As depicted in Figure 1A, the body joints were defined at the following locations: the hip joint (A′) connecting OA with O′A, the ankle joint (B′) connecting O′B with CB, and the head of the fifth metatarsophalangeal joint (C′) that was measured from BC with respect to the horizontal (Dionisio et al., 2006; Sriwarno et al., 2006). The value of body joint flexion was measured manually from the extracted photograph. The knee joint angle was not measured due to the requirement of the experiment’s protocol that asked the subjects to fully flex the knee joint; therefore, flexion was relatively unchanged during squatting. In this position, the subjects had to rest the buttocks on the upper part of the calcaneus.

Bipolar surface electrodes (TSD150B, inter-electrode spacing of 20 mm, surface electrode stainless steel pads with diameters of 11.4 mm, a band pass filter at 20–500 Hz) were placed only on the right lower limbs of the rectus femoris (RF), tibialis anterior (TA), gastrocnemius (G), soleus (SOL), and extensor digitorum brevis (EDB) after the skin was cleaned with ethanol. MP150 workstation hardware and AcqKnowledge software (BIOPAC System, Inc. Santa Barbara, Calif.) were used to amplify and store the electromyography (EMG) signals at a sampling rate of 1000 Hz. The last ninety sec of recorded data were picked up and sixty sec out of the selected data which were free from any noise were analyzed. To allow for comparison of EMG intensity between muscles, the amplitude data were normalized to the EMG values acquired during a maximal hip and knee flexion (Zhang and Ng, 2007), ankle dorsiflexion and plantarflexion, and toes extension effort as a maximum activation (MA). This was done by asking each subject to adopt deep squats; therefore, the hip and knee joint were able to achieve full flexion. In this condition, the subjects were asked to raise the heel 10 times until unable to complete full motion in order to measure the maximum EDB activation. Collected EMG data were converted to root mean square.

A 50×50 cm force platform was designated by placing four miniature transducers (type LMA-A-P, capacity 1kN, Kyowa Electronic Instrument Co. Ltd.) underneath the four edges of the platform to determine the vertical force distribution from the feet during squatting. Data were sampled and set at 1750 Hz for 60 s of recording synchronized with the EMG data. The recorded data were re-calibrated when the foot slope was applied to the platform. Footmarks were drawn on the platform to indicate the position and orientation of the feet. In order to avoid an anterior sliding effect, a tiptoe stopper was placed in front of the foot slope in the TTS condition (Fig. 1C). The GRF distribution as a representation of COP displacement was plotted in the anterior-posterior (A-P) and right-left (R-L) directions and was presented in the sway trajectory which has been used in previous investigations (Chiari et al., 2002; Shimizu and Andrew, 1999; Uetake et al., 2004) and the standard deviations of COP displacement in A-P and R-L direction were averaged for statistical analysis. One-way ANOVA was employed to test the effect of squatting strategy on the %MA of EMG, body joint angles, GRF, and feet projection. A post-hoc test was conducted to examine the significant effect of the two conditions on the squatting strategies.

**Results**

In this present study, we conducted experiments employing subjects with a wide range of body types (Table 1). Most subjects were normal weight (50%), 37.5% were over-weight, and one subject was judged to be obese. As depicted in Fig. 2, a significant effect was found on the A′ and C′ joint which showed in the higher effects between TT and FS (p<0.01) while a small effect occurred between TT and TTS (p<0.05). FS was found to be significant with TTS (p<0.05). No effect was found on the B′. As shown in Fig. 3, when the TT condition was achieved, although the foot angle shown at FA increased, we did not find any significant effect. The length of BOS showed a drastic decrease when the subjects performed TT. The TT conditions significantly affected the length of BOS (p<0.01 to FS and TTS). We found a small effect between FS and TTS (p<0.05).

The average EMG of all recorded muscles across the
subjects was calculated for the three different squatting strategies as depicted in Fig. 4. The ANOVA revealed the strong effects of the squatting strategy on the anterior muscles RF, TA, and EDB. The post-hoc analysis showed a decrease in the amount of %MA of RF between FS and TT ($p<0.05$) and between FS and TTS ($p<0.01$). No significant difference was found between TT and TTS ($p>0.05$). TA also demonstrated a similar effect that was deactivated from FS to TT ($p<0.01$) and FS to TTS ($p<0.01$), whilst no difference was found between TT and TTS ($p>0.05$). The greatest activity of EDB significantly increased at TT in comparison with FS ($p<0.01$).

The presence of the foot slope at TTS reduced the activity of EDB significantly ($p<0.01$) at about 47%MA, but no significant difference was found between FS and TTS. The main effect of squatting strategy was also demonstrated by the posterior muscles as a pair of G and SOL. A similar pattern of activities showed a significant difference between TT and TTS ($p<0.05$ for G and $p<0.05$ for SOL). No effect was found between FS and TT on both muscles.

The mean data across all subjects for the COP displacement of squatting strategies are shown in Fig. 5. For the plots of both COP displacements in A–P and R–L direction, it can be clearly seen that the greatest displacement effects exist between TT and FS ($p<0.01$ for A–P and $p<0.01$ for R–L) as well as between TT and TTS ($p<0.01$ for A–P and $p<0.01$ for R–L). ANOVA revealed no effect between FS and TTS. Since the position of the footmarks was standardized in order to avoid movement, it was found that the oscillation of COP displacement moved anteriorly from FS to TT, respectively, as the heel height increased (Fig. 6A). In contrast, the oscillation of the COP displacement was not clearly different in the right-left direction among squatting strategies (Fig. 6B). As depicted in Fig. 7, the influences of the greatest oscillation of COP displacement in the sway trajectory
occupied a wider area at TT than at FS and TTS. Since the area of sway trajectory was calculated by multiplying the standard deviation of COP displacement between A-P and R-L direction, the boundaries of sway trajectory were demonstrated to be more expansive on average at TT than at FS and TTS (Fig. 8).

Discussion

In most cases, prolonged squatting caused the overload of leg muscles resulting in the highest level of discomfort during deep squatting, as has been reported in previous studies (Diee et al., 1997; Sriwarno et al., 2006). The results of this experiment showed that performing TT most strongly influenced the parameters while the presence of the foot slope regained the condition at FS but with an improvement as shown at TTS. From this finding, we draw attention to the tiptoe strategy that influences postural achievement, EMG, and balance control in comparison with the ankle strategy. Seen in terms of a static posture that is performed without any support, squatting is sometimes considered a form of standing since the feet must support the whole body weight. Thus, the balance characteristics of squatting showed some similarity with the pattern involved in standing. However, the obvious difference between squatting and standing regarded the requirement for the buttocks to rest on the calf region; therefore, the distance between the head and the floor decreased, whereas squatting requires deep hip, knee, and ankle flexion. Behaviorally, once TT was achieved, the hip and head of the metatarsophalangeal joint angle increased as the heel lifted up and affected the angle between the feet, causing it to be more open. Under this condition, Shimizu and Andrew (1999) suggested that the change of body angle was closely related to segmental body linkage coordination, which occurred as a compensation of balance control; therefore, the center of gravity is maintained within the BOS.

Shifting the posture from FS to TT significantly reduced both the strength of the anterior muscles (RF and TA) and increased the angle of A’ and C’. According to the photographic analysis, the posture achieved in this tiptoe strategy caused the thigh to be parallel with the floor. Although unexpected, this may explain why the ankle joint decreased due to increased ankle torque as a sum of all the vertical forces. This main effect was consistent with the result of previous investigations that widening the hip angle decreases the RF muscle activity which functions to flex the hip joint (Nishiwaki et al., 2006; Nordin and Frankel, 2001; Perotto et al., 1994; Yamada and Demura, 2004). In the ankle strategy, TA becomes important to transport the whole body angularly forward with respect to the ankle joint as a center of rotation. This ankle dorsiflexion activated the TA into the highest activation at FS. As the heel was lifted to achieve tiptoe squatting, the plantar flexion showed a counter action to lower the activity of TA at TT whilst the center of rotation is shifted from the B’ to the C’ joint. During tiptoe squatting, the buttock’s height increased and the hip joint provided abdominal room over the almost-horizontal thigh. The increase of A’ and C’ and the decrease of muscle strength in the RF and the TA may explain why people who lack the ability to perform deep squats prefer to lift the heel due to abdominal size or muscles stiffness around the ankle. The calf muscles, SOL and G, combine to form the Achilles tendon, inserted into the calcaneus, and are the strongest plantarflexors of the ankle (Nordin and Frankel, 2001; Tansey and Briggs, 2001). During the firing of ankle plantar flexion, SOL and G functioned to brake anterior movement caused by the TA over the ankle strategy which was shown at FS and TTS. The highest tension of these muscles at TT indicated that the TA in the tiptoe posture was deactivated while the heel was lifted.

As shown in Fig. 4, since the function of the EDB was known to dorsiflex the second, third, and fourth metatarsophalangeals (Nordin and Frankel, 2001; Tansey and Briggs, 2001), the lifting of the heel activated the EDB and shifted the pressure towards the metatarsophalangeal head. Although most EMG data showed a similar decreasing trend, an unexpected though interesting finding regarding the EDB demonstrated an increase at TT of almost 39%MA. This means that the shifting of muscle activation caused the whole body to shift angularly forward. During decreasing activity of the TA at about 53.2%MA, EDB showed to increase at TT. Also shown by the feet projection, the length of the BOS was reduced at TT by about 50% compared to other conditions. Although a significant difference in the FA did not appear (Fig. 3), the increase of the foot angle somehow lengthened the BOS at TT, leading to a more stable balance. The activity of the EDB at TT showed significant influence in controlling the squatting balance; therefore, the C’ joint was maintained in metatarsophalangeal dorsiflexion while the flexor digitorum brevis (not measured) was co-activated as a counter action to keep the COP displacement within the BOS (Nordin and Frankel, 2001). Regarding the role of the TA and the EDB in dorsiflexion, it is suggested that shifting the squatting strategy from FS to TT shifted the role of the muscles’ balance control from the TA in the ankle to the EDB in the head of metatarsophalangeal. As a counterbalance, the flexor digitorum
brevis played the role of proximal interphalangeal flexor in order to prevent the body from falling forward. These findings confirmed those of the previous studies showing that the mechanism of shifting the burden of the muscles during angular forward movement was controlled by the coordination of anterior and posterior lower limb muscles (Norioka et al., 2005; Yamada and Demura, 2004).

Since the oscillation of COP displacement indicates the level of balance control, the large margin of sway trajectory often corresponds to postural instability (Murray et al., 1967; Takeuchi et al., 2007). Most current measurements of stability are related to the excursion of the COP boundary, and a small COP boundary is then considered to indicate a state of good balance (Oliveira et al., 1996; Uetake et al., 2004). The increased oscillation in the COP displacement at TT might relate to the boundaries of COP distribution being higher than at FS or TTS as shown in sway trajectory (Fig. 8). These effects seemed to act as a counterbalance along A-P and R-L movement, as shown in Fig. 7. As described above, the trajectory boundaries of COP displacement at TT were significantly wider than at both FS and TTS. However, this finding suggests that the effect occurring under the TT condition indicates an imbalanced posture during tiptoe strategy according to the wider area of occupation. Since static squatting could be equated to standing in terms of non-supported vertical posture, our results are generally consistent with those of previous studies in which the tiptoe posture contributed to posture instability (Dionisio et al., 2006; Hof et al., 2005; Shimizu and Andrew, 1999).

Squatting on a sloping surface as shown at TTS is equivalent to squatting on an uneven floor because the level of the slope constitutes a certain height for maintaining the squatting posture. The presence of a 15° inclination causes the moment to push the foot down behind the stopper. Although the presence of the foot slope was derived from the idea of raising the heel, in fact, the rotation center of dorsiflexion was brought back from the head of the metatarsophalangeal joint to the ankle joint. According to the variation of muscle activation, elevating the heels increased the calcaneus height that physically influenced the activity of the muscles surrounding the foot. The tiptoe position on a foot slope demonstrated a reduction of muscular load, and the degree of stability derived from COP displacement became as high as that shown at FS. Concerning squatting strategy, it is suggested that the presence of a 15° foot slope allowed the lower body muscles to relax. These findings indicate the necessity of the appropriate foot slope angle regarding the physical limitations of the obese and elderly in maintaining their balance in the deep squat posture. However, as the heel height increased, the center of mass increasingly moved forward, and this postural load acted to reduce muscle strength in the rectus femoris and anterior tibialis muscle and may have resulted in a decrease of discomfort although the load on the ankle and feet increased. One possible implication for these results is that the overweight, obese, or pregnant would prefer to perform tiptoe squatting probably due the need of proper abdominal room to reduce pressure on the waist region during hip flexion, thereby decreasing postural discomfort.

According to the results from the short duration of the squatting examination, furthermore, the effect of prolonged squatting on postural discomfort would imply a risk of injury. It has been suspected that such prolonged squatting, in which feet fully contact the floor level, would gradually cause musculoskeletal complaint in individuals (Chung et al., 2003). In this condition, the subjective discomfort repeatedly increases after 6–8 min from the beginning of the task. Also reported by Cai and You (1998), the difficulties encountered during adopting full squatting were identified as numbness in the lower legs, difficulty in maintaining balance, and difficulty in conducting the standing up movement. Full squatting somehow can prevent blood from flowing properly, which makes the subjects feel numb at some part of the shank. Postural improvement occurred in deep squatting aimed at reducing muscular load, especially of the lower extremity muscles, which were suspected as being a main contributor of discomfort in squatting postures.

In summary, maintaining balance in a tiptoe position appeared to require the complex coordination of shifting activity between the anterior and posterior limb muscles. Elevating the heel tends to lengthen the COP displacement during tiptoe strategy but the accompanying decrease of the rectus femoris and tibialis anterior muscles increases the activity of the extensor digitorum brevis. In order to reduce the incidence of musculoskeletal problems, allowing the feet to rest on a sloping surface in order to decrease the muscular load should be considered in the areas of occupational safety and health.

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Correspondence to: Andar Bagus Sriwarno, Graduate School of Science and Technology, Chiba University, 1–33 Yayoi-cho, Inage-ku, Chiba 263–8522, Japan
Fax: +81–43–290–3084
e-mail: andarbugs@yahoo.com/asriwarno@graduate.chiba-u.jp