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Research article

The kinetics and stiffness characteristics of the lower extremity in older adults during vertical jumping

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Abstract

The purpose of this study was to examine the modulating effects of age on lower limb stiffness and net muscle joint activity degeneration when performing a functional activity involving SSC. Seven young males and seven older males were recruited as subjects for this study. A high-speed camera and a force plate were synchronized to collect the biomechanical parameters. The kinetic parameters were calculated with the inverse dynamics process. The stiffness of lower limbs was calculated with the spring-mass model. The Student's t-test was used to test the differences of two age groups. Statistical significance was set at $\alpha = 0.05$. The present research showed that the older group produced a smaller peak net muscle joint moment at hip and knee. There were no differences in leg stiffness, hip stiffness, and ankle stiffness between the two age groups. Knee stiffness was smaller in the older group. In elderly adults, reduced muscle strength in the lower limbs, especially in the hip and knee, and reduced stiffness of the knee, influence the basic functions of human life and increase the risk of injury. Differences in lower extremity kinetics and stiffness in elderly adults during SSC movement may have implications for new preventive measures.

Key words: Aging, biomechanics, inverse dynamic, spring-mass model.

Introduction

Muscle strength and muscle power are fundamental to the performance of tasks of daily living, such as walking, climbing up and down stairs, and prevention of falls etc. (Bassey et al., 1992; Izquicrdo et al., 1999). Previous studies using isokinetic and isometric tests have shown that the elderly have significantly decreased muscle strength (Borst, 2004; Cress et al., 2004). However, since daily activities often involve complex, multi-joint motions, and isotonic and isometric tests can only detect changes of muscle strength of individual joints during isolated joint motion, the detected muscle weakness of one joint cannot be used to deduce the changes of the muscle forces and the associated compensatory changes at other joints in the elderly during multi-joint activities. Therefore, in the study of motion of the elderly, a better understanding of the influence of muscle weakness of each individual joint on the performance of dynamic functional activities should be achieved through dynamic multi-joint motion tests.

Jumping has often been used for muscle strength testing of the lower extremities in the motion analysis studies of different age populations (Elvira et al., 2001). In a comparative study on the performance during countermovement jumping (CMJ) and squat jumping (SJ), Paasuke et al. (2003) indicated that older females did not show the stretch-shortening cycle (SSC) during CMJ. From the temporal characteristics of the biomechanical parameters of the lower extremities in the elderly during SJ, Haguenauer et al. (2005) also showed that the proximal-distal sequence was not present in the elderly during jumping. However, the internal dynamic variables, such as net muscle joint moment and power at each joint of the lower extremities, were not included in the previous studies on the elderly during jumping. Therefore, muscle dynamics analysis of the joints of the lower extremities can be very useful in determining the net muscle joint moment at each joint during dynamic muscle strength tests and thus lead to a better understanding of dynamic muscle strength.

In organism, the overall muscle stiffness is determined by the properties of the musculoskeletal system such as the stiffness of ligaments, tendons, cartilage, muscle, bone and joints (Latash and Zatsiorsky, 1993; Owen et al., 2005). Meanwhile, muscle stiffness is determined by the spring-like characteristics of the muscle and the neural feedback system and can be modulated by controlling muscle activity and by neural system feedback (Cavagna et al., 1977; Cannon and Zahalak, 1982; Derrick, 2004; Farley and Gonzalez, 1996; Farley et al., 1993; 1998; Farley and Morgenroth, 1999; Full and Farley, 2000; Liu et al., 2006). Therefore, studying muscular stiffness elucidates the mechanisms of adaptation and modulation in the human body. In recent years, the spring-mass model has been applied in the study of human performance, injury and regulation (Farley and Gonzalez, 1996; Farley and Morgenroth, 1999). This model was developed based on the elastic characteristic of the human musculoskeletal system. It integrates the muscle fibers, tendons, ligaments and the activity of all the muscles of the lower extremities into a simple linear spring. The resultant force transmitted in the spring is equal to the product of the spring constant (k_{leg}) and linear displacement ($F = k_{leg}\ \Delta y$), and the spring constant is called leg stiffness. Applying a similar concept to angular joint dynamics, the joint stiffness can be defined because the resultant moment at a joint is equal to the product of the torsional spring constant and angular displacement of the joint ($M = k_{joint}\ \Delta\theta$) (Brughelli and Cronin, 2008; Farley et al., 1998; Farley and Morgenroth, 1999; Full and Farley, 2000).

Furthermore, appropriated muscular stiffness

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provides a mechanism of prevention of injury during activity, and the increase of muscle and joint stiffness increases joint stability, which helps to sustain rapidly and effectively the sudden changes of the joint. Hence, insufficient stiffness may destabilize joint motion and increase the incidence of soft tissue injury (Butler et al., 2003; Flanagan and Harrison, 2007; Granata et al., 2002; Kuitunen et al., 2007; Yoon et al., 2007). For this reason, study of the characteristics of the elderly during dynamic multi-joint activities in terms of the kinetic parameters of the lower limbs and the stiffness of lower limb will be helpful for a better understanding of this ageing phenomenon. From the above literature review, it is unclear how the lower limb stiffness is changed to accommodate for the reduced muscle strength of the elderly when performing dynamic multi-joint activities. Therefore, this study examined the modulating effects of age on lower limb stiffness and net muscle joint activity degeneration when performing a functional activity involving SSC.

Methods

Subjects

Seven young male (18.0 ± 0.3 yrs, 1.75 ± 0.06 m, 70.8 ± 9.92 kg) and 7 older male adults (67.1 ± 2.5 yrs, 1.63 ± 0.08 m, 66.7 ± 8.87 kg) participated in the current study. None of the subjects undertook any specific exercise training or had any sports injury in their lower extremities. They all could perform daily activities normally. Before the experiment, all subjects read the experimental notice, gave written informed consent, and completed a health survey.

Participants were required to stand on the force plate with their hands on their hips, and the instruction given to the participants was “jump as high as you can”. All participants warm up with a standard procedure before the formal experiment. Each participant had to complete three successful trials, and the highest jump was selected for analysis.

A MegaSpeed high-speed camera (125 Hz) was synchronized with an AMTI force plate (1250 Hz) to collect the biomechanics parameters. Segment data for foot, leg, thigh, and head and trunk (HAT) were calculated based on Dempster (1955) segment parameters. Five body landmarks were fixed on the participants’ acromion, greater trochanter, lateral epicondylus, lateral malleous, and tip of the foot at the height of the metatarsals on the left side; and one reference point was fixed on the force plate. All these points were digitized and framed by a Kwon3D system. A Butterworth Digital Recursive Filter was used to filter the random noise in the process of digitization (fourth-order lower-pass with a cut-off frequency of 8 Hz). The ground reaction forces (GRF) and center of pressure were collect by a KwonGRF system.

The net muscle joint moment (M), net muscle joint power (P), and net muscle joint work (W) were calculated with the inverse dynamics process (Winter, 2005). The leg stiffness (k_{leg}) was calculated by the formula: ($Fy_{hip\text{-}lowest}$) / (ΔY_{hip}). The $Fy_{hip\text{-}lowest}$ indicated the vertical GRF while the hip was at the lowest position. The ΔY_{hip} was the vertical displacement of the hip from the start to the point at which the hip was at its lowest. The joint stiffness (k_{joint}) was calculated by the formula: ($M_{joint\text{-}minimally}$) / ($\Delta\theta_{joint}$). The $M_{joint\text{-}minimally}$ was the net muscle joint moment while the joint was maximally flexed. The $\Delta\theta_{joint}$ was the angular displacement of the joint from the start to the point at which the joint was at its minimal flexion.

In this study, the jump height was normalized on the basis of the height of participant, and *Height* was used as the unit. The normalized GRF was the measured GRF divided by the subject’s body weight, and *BW* was used as the unit. The normalized net muscle joint moment was the net muscle joint moment divided by the subject’s body weight, and $Nm\cdot kg^{-1}$ was used as the unit. According to the concept of inverse dynamics (Winter, 2005), positive net muscle joint moment was defined as extensors activity, while negative net muscle joint moment indicates the activity of the flexors. The normalized net muscle joint power was the net muscle joint power divided by the subject’s body weight, and the unit used was $W\cdot kg^{-1}$. The net muscle joint power was positive when muscles contracted concentrically and negative when muscles contracted eccentrically. The normalized displacement of the hip joint was defined as the vertical displacement of the hip joint divided by the subject’s leg length, and the unit was ‘Length’. The normalized leg stiffness was defined as the GRF divided by the normalized displacement of the hip joint, and the unit was *BW/length*. The normalized angular stiffness was defined as the net muscle joint moment divided by the joint angular displacement, and the unit was $Nm\cdot kg^{-1}/rad$. The movement times were the absolute time calculated as the ratio of the total movement time. The total movement time was estimated by counting the second from initiation of movement to the moment of take off.

All the calculated variables were tested using an independent t-test for the differences between young and older subjects during vertical jumping. A significance level of $\alpha = 0.05$ was set for all statistical tests.

Results

The normalized jump height in the older group (0.17 ± 0.03 Height) was significantly lower than that of the young group (0.29 ± 0.03 Height, $p < 0.05$). The peak GRF was significantly smaller in the older group ($p < 0.05$, Table 1). Compared to the young group, the older group not only had smaller peak hip and knee joint moments ($p < 0.05$) but also significantly decreased peak net muscle joint powers at the hip, knee and ankle ($p < 0.05$).

Table 2 showed the mean relative times at four muscle movement stages (i.e., FCC: flexors' concentric contraction, EEC: extensors' eccentric contraction, ECC: extensors' concentric contraction, and FEC: flexors' eccentric contraction) at three joints for both groups. In the movement times, no significant differences were found between two groups at ankle ($p > 0.05$). There was significant differences were found in the movement times of hip and knee between two groups ($p < 0.05$). No FCC of hip was found in older group. The movement times of hip EEC and knee FCC in older group were significant longer ($p < 0.05$). In addition, the older group assigned shorter time of hip ECC, knee EEC, and knee ECC ($p < 0.05$).

Table 1. Kinetic parameters of lower limbs during vertical jump. Data are means (±SD.

		Young Group	Older Group
Maximum normalized Fy (BW)		1.20 (.06)	1.02 (.13) *
Maximum normalized M ($Nm\cdot kg^{-1}$)	Hip	2.45 (.36)	1.79 (.32) *
	Knee	1.52 (.16)	.81 (.26) *
	Ankle	1.86 (.18)	1.61 (.23) *
Maximum normalized P ($W\cdot kg^{-1}$)	Hip	10.80 (1.27)	5.39 (1.79) *
	Knee	6.19 (1.18)	2.58 (.99) *
	Ankle	16.91 (3.21)	10.01 (2.47) *
Normalized total W ($J\cdot kg^{-1}$)	Hip	2.73 (.73)	1.54 (.66) *
	Knee	1.62 (.27)	.83 (.39) *
	Ankle	1.80 (.17)	1.19 (.39) *

* significant difference between groups, p < 0 .05

Table 3 shows the parameters of the normalized leg muscular stiffness during standing vertical jumping. Figure 1 shows the relationship between the GRF and the vertical displacement of the hip for two typical subjects from the two age groups. The experimental results (Table 3) showed that the vertical displacement of the hip and the vertical GRF of the older group were all significantly smaller than those of the young group ($p < 0.05$) when the hip joint was at the lowest position. There was no significant difference between these two groups in leg stiffness ($p > 0.05$). The figure 1 shows that the vertical GRF and the vertical displacement of the hip are greater in the young subjects than in the older subjects in the crouch phase. Therefore, although the line a-b of the force-deformation relation curve is shorter in the older subjects than in the young subjects, the slopes are similar.

Table 3. Parameters of leg spring-mass model during vertical jumping. Data are means (±SD).

	Young Group	Older Group
Normalized $Fy_{hip\text{-}lowest}$ (BW)	1.21 (.09)	.97 (.14) *
Normalized ΔY_{hip} (Length)	.41 (.07)	.31 (.08) *
Normalized k_{leg} (BW/Length)	3.03 (.56)	3.25 (.86)

* significant difference between groups, p<0 .05

Table 4 shows the normalized angular stiffness of each joint during standing vertical jumping. The relationship between the net muscle joint moment and the angular displacement for the hip, knee, and ankle of two typical subjects from the two age groups are shown in Figures 2, 3 and 4. The results (Table 4) show that the young group had greater angular displacement of the hip and muscular stiffness of the hip and knee ($p < 0.05$). The angular stiffness in knee joint of the older group was significantly reduced ($p < 0.05$). There were no differences in joint stiffness for hip and ankle between groups ($p > 0.05$). Figure 2 shows that the net muscle joint moment and the angular displacement of the hip are greater in the young subjects than in the older subjects in the crouch phase. Although the line a-b of the moment–deformation relation curve for the hip was shorter in the older subjects than in the young subjects, the slopes were similar. Figure 3 shows that the net muscle joint moment of the knee is greater in the young subjects than in the older subjects in the crouch phase. However, the angular displacement of the knee flexion is similar. Therefore, the slope of the line a-b of the moment–deformation relation curve for the knee is flatter in the older subjects than in the young subjects.

Discussion

The sequence of eccentric muscle action immediately followed concentric action is defined as SSC, which is a natural component of muscle function in many daily activities. Maximal voluntary contraction and SSC is involved during CMJ, thus revealing the muscular strength and the unique activation strategies of the neuromuscular system of the lower extremities (Enoka, 1996; Kubo et al., 1999; Liu et al., 2006). Hence, peak GRF and peak net muscle joint moment during vertical jumping are important indices of muscular strength in the lower extremities. This study found that, compared to younger subjects, elderly subjects have maximal voluntary CMJ with lower

Table 2. The mean relative times (%) at four muscle movement stages. Data are means (±SD).

		Young Group	Older Group
Hip	Flexors' Concentric Contraction	13.50 (6.88)	.00 (.00) *
	Extensors' Eccentric Contraction	41.04 (9.23)	69.37 (5.12) *
	Extensors' Concentric Contraction	36.81 (2.13)	28.74 (3.66) *
	Flexors' Eccentric Contraction	1.28 (1.94)	1.88 (1.70)
Knee	Flexors' Concentric Contraction	6.85 (4.44)	28.13 (13.72) *
	Extensors' Eccentric Contraction	58.25 (5.43)	42.29 (14.45) *
	Extensors' Concentric Contraction	30.39 (3.12)	22.67 (6.63) *
	Flexors' Eccentric Contraction	4.50 (2.13)	6.91 (6.10)
Ankle	Flexors' Concentric Contraction	.00 (.00)	.00 .00)
	Extensors' Eccentric Contraction	67.81 (2.49)	71.15 (4.58)
	Extensors' Concentric Contraction	32.00 (2.44)	28.54 (4.71)
	Flexors' Eccentric Contraction	.18 (.48)	.30 (.53)

* significant difference between groups, p<0 .05

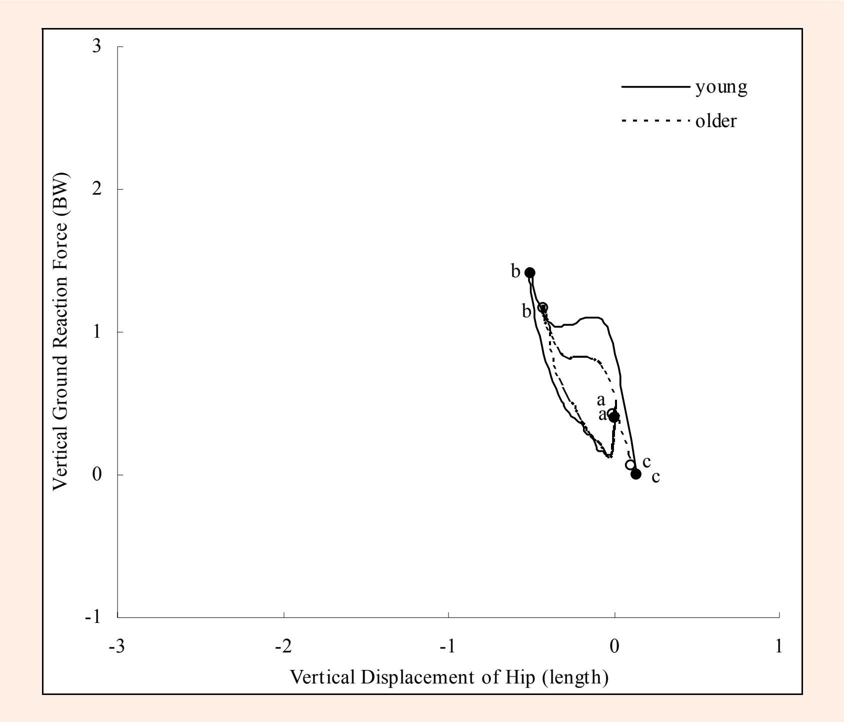

Figure 1. **The force-deformation relation for the leg during vertical jumping. Point *a* indicates that the subject started downward motion. Point *b* indicates that the hip reached the lowest position. Point *c* indicates the moment of take-off. The slope of the line a-b reflects the leg stiffness in the crouch phase.**

peak GRF as well as smaller peak net muscle joint moment at the hip and knee joint. Elderly subjects therefore exhibit lower net muscle joint power and lower total work of the lower extremities during concentric phase of the CMJ. This degraded dynamic muscle strength impairs basic functional activity in elderly. In elderly, this muscle weakness can also severely impair ambulation, particularly balance and stability (Connelly, 2000; Lord et al., 1994).

Further, lower limb stiffness may be affected neuromuscular system activation. During human locomotion, the neuromuscular system adopts adequate muscle activity in different conditions to achieve success in the interaction between organism and GRF, adjusting the stiffness of the lower limbs while in motion could keep the movement in a state of stability (Cavagna et al., 1977; Cannon and Zahalak, 1982; Farley et al., 1998; Farley and Morgenroth, 1999; Full and Farley, 2000). Farely et al. (1998) suggested that the control of joint angular stiffness and segment angles was very important for the modulation of leg stiffness, and that was why one would achieve the same movement pattern. The major findings of this study are that, compared to young subjects, elderly subjects perform maximal voluntary CMJ with less angular stiffness of the knee during CMJ. Leg stiffness and angular stiffness in the hip and ankle did not statistically differ.

However, leg stiffness was determined by vertical GRF and hip displacement, and joint stiffness was determined by net muscle joint moment and angular displacement at the transition from the downward to upward phase during the CMJ. From assessment of the leg stiffness and associated parameters in the elderly during CMJ, the GRF was found to be reduced significantly when the hip joint was at the lowest position, and the displacement of the leg length was also reduced. Hence, although the line a-b of the force-deformation relation curve was shorter in the older group than in the young group, the slopes were similar. The leg stiffness of the elderly was not different from that of the young. The similar phenomenon was in the angular stiffness of the hip, the current study

Table 4. **Parameters of joint spring-mass model during vertical jumping. Data are means (±SD).**

		Young Group	Older Group
Hip	Normalized $M_{\text{hip-minimally}}$ ($\text{Nm}\cdot\text{kg}^{-1}$)	2.40 (.39)	1.71 (.39) *
	$\Delta\theta_{\text{hip}}$ (degree)	94.91 (12.81)	74.87 (15.08) *
	Normalized k_{hip} ($\text{Nm}\cdot\text{kg}^{-1}\cdot\text{degree}^{-1}$)	.03 (.00)	.02 (.00)
Knee	Normalized $M_{\text{knee-minimally}}$ ($\text{Nm}\cdot\text{kg}^{-1}$)	1.48 (.15)	.78 (.28) *
	$\Delta\theta_{\text{knee}}$ (degree)	95.21 (8.34)	88.62 (13.57)
	Normalized k_{knee} ($\text{Nm}\cdot\text{kg}^{-1}\cdot\text{degree}^{-1}$)	.02 (.00)	.01 (.00) *
Ankle	Normalized $M_{\text{ankle-minimally}}$ ($\text{Nm}\cdot\text{kg}^{-1}$)	1.71 (.22)	1.46 (.20)
	$\Delta\theta_{\text{ankle}}$ (degree)	37.18 (1.35)	32.26 (7.51)
	Normalized k_{ankle} ($\text{Nm}\cdot\text{kg}^{-1}\cdot\text{degree}^{-1}$)	.05 (.01)	.05 (.02)

∗ significant difference between groups, $p < 0 .05$

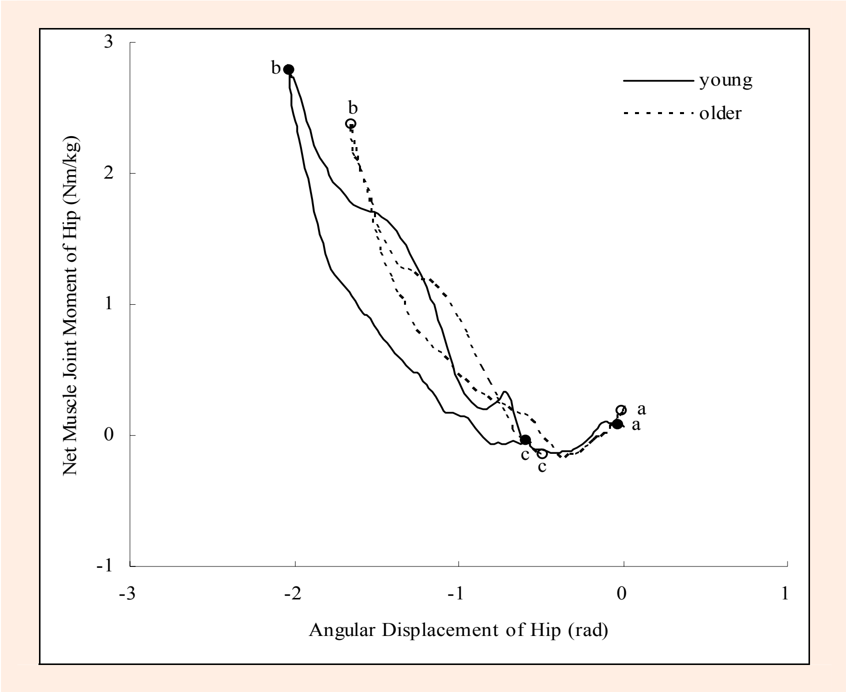

Figure 2. **The moment–deformation relation for the hip during vertical jump. Point *a* indicates that the subject started downward motion. Point *b* indicates that the hip reached the minimal joint angle of flexion. Point *c* indicates the moment of take-off. The slope of the line a-b reflects the joint stiffness of the hip in the crouch phase.**

found that both the net muscle joint moment at the hip joint and the angular displacement of the hip were significantly reduced when the hip was minimally flexed. Hence, although the line a-b of the moment–deformation relation curve was shorter in the older group than in the young group, the slopes were similar. The angular stiffness of the hip in the older group was not significantly different from that of the young. This result suggests that the elderly tended to decrease the leg displacement to modulate leg stiffness in successfully performing the dynamic activity. Otherwise, the older group decreased angular displacement of the hip to modulate the angular stiffness of the hip. Restated, in the elderly, the hip joint stiffens during downward motion. A similar phenomenon occurs during the preparing posture in SJ and downward stepping in the elderly (Haguenauer et al., 2005;

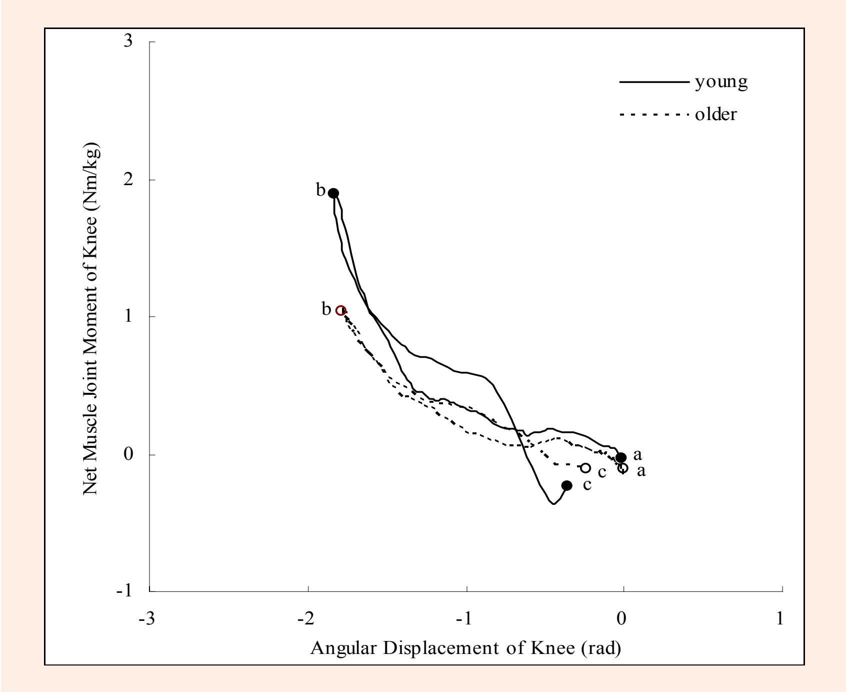

Figure 3. **The moment–deformation relation for the knee during vertical jumping. Point *a* indicates that the subject started downward motion. Point *b* indicates that the knee has reached the minimal joint angle of flexion. Point *c* indicates the moment of take-off. The slope of the line a-b reflects the joint stiffness of the knee in the crouch phase.**

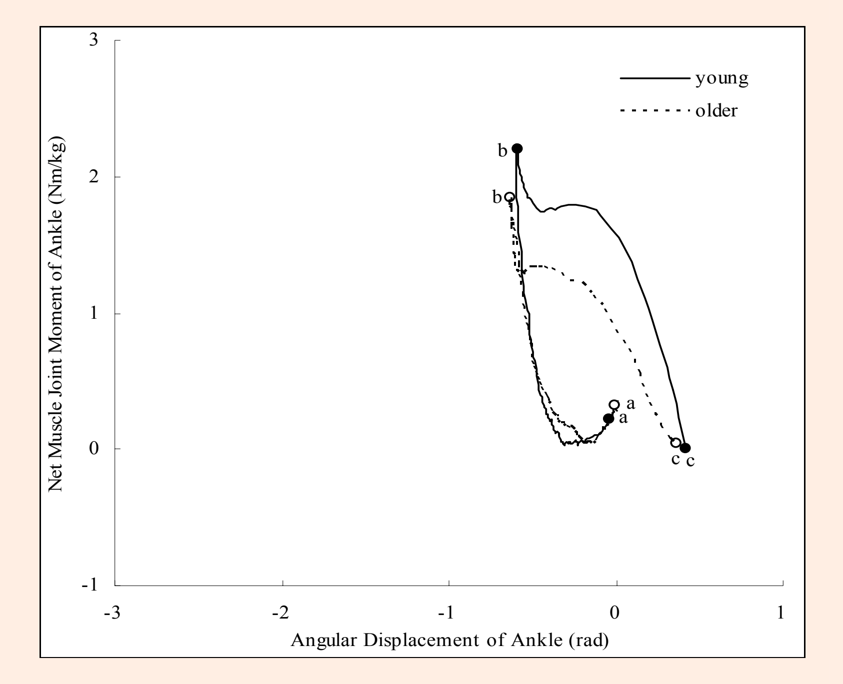

Figure 4. **The moment–deformation relation for the ankle during vertical jump. Point *a* indicates that the subject started downward motion. Point *b* indicates that the ankle has reached the minimal joint angle of dorsiflexion. Point *c* indicates the moment of take-off. The slope of the line a-b reflects the joint stiffness of the ankle in the crouch phase.**

Hortobagyi and DeVita, 2000). The authors suggest that the elderly tend to stiffen the trunk or legs in compensation for impaired neuromotor functions and decreased muscle strength to increase stability. In elderly, this phenomenon elevates antagonist muscles activity, which increases muscle coactivity (Izquicrdo et al., 1999). Elevated muscle coactivity increases joint stiffness: hence, joint stability is also increased in the lower extremities (Baratta et al., 1988). In this study, analysis of net muscle joint moment and power revealed that the elderly do not exhibit concentric flexor contraction in the hip joint at the beginning of the crouch phase. The elderly therefore perform the downward motion using only eccentric contraction of the extensors. Hence, elderly clearly have a longer eccentric contraction period of extensors at the hip joint than young adults. A likely explanation is that the elderly increase antagonist muscles activity to decrease hip flexion; hence, joint stability is increased during the downward motion of CMJ.

However, the elderly showed reduced net muscle joint moment at the knee joint when the knee reached minimum flexion, but the angular displacement of the knee joint was not reduced. This phenomenon caused the slope of line a-b of the moment–deformation relation curve to be flatter in the older group than in the young group. The angular stiffness was reduced significantly. Greater leg stiffness during countermovement motion might be advantageous because it allows greater storage and release of elastic energy to increase the force of motion (Gollhofer et al., 1992; Komi, 1992). Hence, the current study shows that the decrease of knee stiffness was obvious in the older group during the CMJ. This result may be related to the finding of a previous study, that the benefit from SSC during countermovement motion was not obvious in the elderly (Paasuke et al., 2003).

Otherwise, joint stiffness is conducive to angular resistance to torque (Williams et al., 2007). Hence, enhanced joint angular stiffness could resist sudden angular displacement, which is beneficial to joint stability (Flanagan and Harrison, 2007). Butler et al. (2003) suggested that reduced joint angular stiffness may increase the damage to cartilage and ligaments. Therefore, an appropriate amount of stiffness is relevant to the prevention of injury (Kuitunen et al., 2007). The results in the current study suggest that, with decreased muscle strength, the elderly decreased the hip angle to maintain its angular stiffness, a strategy that can help protect the hip joint. Therefore, the elderly reduced the angular displacement of the hip during downward motion to adjust the hip stiffness, but the straighter motion of the trunk could increase the demand at the ACL during downward movement (Decker et al., 2003). Conversely, biarticular muscles cross the hip and knee (*e.g.,* m. semitendinosus and m. biceps femoris). Hence, in the initial downward motion, the longer eccentric contraction of hip joint extensors in elderly may increase concentric contraction of flexors at the knee joint, which would not significantly decrease angular displacement of the knee joint. However, the net muscle joint moment at the knee in the elderly was decreased without decreasing the angular displacement of the knee joint, leading to a significantly decreased angular stiffness, which may be harmful to the knee joint. In a comparative study on leg stiffness in males and females during continuous hopping, Granata et al. (2002) showed that the angular stiffness of the knee joint in females was smaller then that in the males during hopping and suggested that this was the reason why females have a higher risk of knee ligament injuries. In the current study, the reduced angular stiffness of the knee joint in the older group during dynamic activity may be used as the reference for the study of the degeneration of the knee joint in the elderly. Furthermore, the net muscle joint moment and angular stiffness at the ankle joint in the older group were not significantly different from those of the young group, suggesting that no obvious degeneration at the ankle joint function was present in the elderly during the dynamic, mulit-joint motion of the CMJ.

Conclusion

This study of changes in net muscle joint moment and leg stiffness in the elderly during dynamic multi-joint activity revealed significantly decreased lower extremity muscle strength in the elderly, particularly in the hip and knee muscles. This change affects their ability to perform functional daily activities. Older subjects maintain hip angular stiffness by decreasing joint angles in order to protect the joint and to increase stability during movement. However, this mechanism was not observed in the knee joint. Therefore, insufficient angular stiffness of the knee joint may increase the risk of knee injury during a functional activity involving SSC.

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Key points

- The present research showed that the older group reduced muscle strength in the lower limbs, especially in the hip and knee, and reduced stiffness of the knee, influence the basic functions of human life and increase the risk of injury.
- There were no differences in leg stiffness, hip stiffness, and ankle stiffness between the two age groups.
- Older subjects maintain hip angular stiffness by decreasing joint angles in order to protect the joint and to increase stability during movement.
- In elderly adults, insufficient angular stiffness of the knee joint may increase the risk of knee injury during a functional activity involving SSC.

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