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Age dependency of neuromuscular function and dynamic balance control

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Abstract

The purpose of the present study was to examine whether static and dynamic balance control are related to neuromuscular function and ageing. For this purpose, we constructed a new dynamic balance measurement system that simulates natural falling. Ten young (age 21–31 years) and 20 elderly (age 60–70 years) men participated in the experiment. Maximal isometric torque (MVC) and activation level were measured from the quadriceps and plantar flexor muscles. The H-reflex, V-wave, and maximal M-wave were measured from the soleus muscle. In dynamic balance control, anterior-posterior centre-of-pressure swaying was 74 ± 8.1 mm in the young men and 91.5 ± 19.4 mm in the elderly men ($P < 0.05$), whereas in the static condition there were no significant differences between the two groups. Knee extension MVC (young: 181 ± 42 N $\cdot$ m; elderly: 135 ± 39 N $\cdot$ m; $P < 0.01$), torque after 500 ms (young: 147 ± 36 N $\cdot$ m; elderly: 108 ± 39 N $\cdot$ m; $P < 0.05$), and activation level (young: $96.2 \pm 0.8\%$; elderly: $93.8 \pm 2.1\%$; $P < 0.01$) were higher in the young than the elderly men; no differences were observed in plantar flexion. The amount of re-stabilization after a sudden disturbance seems to be an age-related phenomenon, which is seen as a connection between balance control and rapid force production.

Keywords: *Balance, ageing, muscle strength, H-reflex*

Introduction

Functions of the neuromuscular system, such as maximal neural activation and muscle performance, are known to decrease with ageing, particularly after the sixth decade (Hakkinen, Pastinen, Karsikas, & Linnamo, 1995; Narici, Bordini, & Cerretelli, 1991). Degeneration of the neuromuscular system is one of the main reasons for impaired balance control during ageing and therefore it can increase the number of falls in elderly people (Wolfson, Whipple, Amerman, Kaplan, & Kleinberg, 1985; Woollacott, Inglin, & Manchester, 1988). It has been suggested that fall-related injuries are a more common cause of fractures than, for example, osteoporosis (Kannus & Parkkari, 2006), highlighting the importance of fall prevention. Age-related reductions in muscle strength can be caused by the degeneration of fast motor units and muscle atrophy (Thompson, 1994; Vandervoort, 2002). From a functional perspective, ageing may result in lower mean motor unit firing rates (Connelly, Rice, Roos, & Vandervoort, 1999), decreased Ca^{2+} release in the sarcoplasmic reticulum (Delbono, Renganathan, & Messi, 1997), slowing of the speed of myosin-driven actin filaments (Hook, Sriramoju, & Larsson, 2001), decreased frequency of miniature end-plate potentials (Alshuaib & Fahim, 1991), and decreased M-wave peak-to-peak amplitudes (Hicks, Cupido, Martin, & Dent, 1992).

Balance control may also be related to changes in motoneuronal excitability. Tokuno and colleagues (Tokuno, Carpenter, Thorstensson, Garland, & Cresswell, 2007) suggested that the H-reflex is modulated during static postural sway. These authors found that during additional plantar flexor activation, depolarization of the motor neuron pool via synaptic transmission was easier to achieve. During backward sway, the efficacy of the Ia pathway decreased, probably because of increased pre-synaptic inhibition. Consequently, the post-synaptic potential was reduced. Angulo-Kinzler and colleagues (Angulo-Kinzler, Mynark, & Koceja, 1998) proposed that the H-reflex is modulated in

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different body positions, and therefore this might have effects on balance control. The same authors found that control strategies change with ageing, which may also have an effect on balance control. There is some evidence to suggest that H-reflex activity may decrease during ageing (Scaglioni et al., 2002). Scaglioni and colleagues (Scaglioni, Narici, Maffiuletti, Pensini, & Martin, 2003) suggested that decreased H-reflex activity is caused by neural degeneration. The amount of pre-synaptic inhibition may increase with ageing, and may result in lower H-reflex amplitudes (Morita et al., 1995). Within the central components, age-related changes are less clear. Vandervoort and McComas (1986) did not find significantly lower activation levels of the plantar flexor muscles between young and old individuals. Although, it has been also suggested that ageing can cause changes in the central nervous system, and reduce neural drive (Enoka, 1997; Izquierdo et al., 1999b). These changes may have serious consequences for static and particularly dynamic balance control during sudden perturbations.

Balance control is a complex phenomenon that is associated with several human functions. It has been proposed that posture maintenance requires (a) sensory information to detect orientation and motion, (b) selection of an appropriate response to maintain balance, and (c) activation of the muscles that can overcome balance disturbances (Enoka, 2001). Balance is usually measured using static balance tests or different kinds of dynamic tests, such as stair-climbing or force plate tests (Bean, Kiely, LaRose, Alian, & Frontera, 2007; Holviala, Sallinen, Kraemer, Alen, & Hakkinen, 2006). Rankin and colleagues (Rankin, Woollacott, Shumway-Cook, & Brown, 2000) used a platform that moves forward and backward during dynamic balance tests. They found that muscle activation was reduced during cognitive tasks, suggesting that less attentional space was available during balance control. However, it has been demonstrated that static balance tests do not necessarily reveal balance disorders or age-related differences as clearly as dynamic balance measurements (Baloh et al., 1994).

In natural situations, falling is usually caused by a sudden perturbation, such as on a slippery road. In perturbation situations, the control response has been suggested to originate from the ankle muscles, leading to knee and hip muscle activation during more powerful perturbations (Kim & Robinson, 2005). It has been shown previously in elderly people that strength properties decrease with age (Häkkinen et al., 1998). Therefore, the recovery of balance from such perturbations may be related to the function of the neuromuscular system, in particular to the ability to rapidly produce force. The aim of the present study was to examine age-related differences in static and dynamic balance control, and the relationship between balance control and the neuromuscular system. We developed a new dynamic balance measurement system that is able to produce sudden balance disturbances to determine whether age-related differences in balance control would be shown more clearly in dynamic than in static conditions. It was hypothesized that due to neuromuscular degeneration, the elderly would have poorer balance control, and that this would be seen more clearly in response to sudden balance disturbances. Neuromuscular function of the quadriceps and triceps surae muscle groups was assessed based on measurements of torque production, spinal excitability, and activation level.

Methods

Participants

Altogether, 30 male volunteers (10 young aged 26.8 ± 2.7 years; 20 elderly aged 64.2 ± 2.7 years) participated in this study. All participants signed an informed consent and were aware of the protocol and possible risks of the study. The participants underwent a medical examination by a physician before taking part in the study. They were also advised of their right to withdraw from the study at any time. The study was conducted according to the Declaration of Helsinki, and was approved by the Ethics Committee of the University of Jyväskylä.

Test protocol

To minimize the effects of learning on the day of testing, the participants attended a 3-day pre-study period, where they were familiarized with the test equipment and measurements. It was anticipated that dynamic balance measurements would improve significantly after familiarization. After the measurements, the participants performed a 3-month strength training programme, and it was important to keep the effects of learning minimal in these pre-training measurements. Body composition was measured before the participants performed a 10-min cycling warm-up at 80 W. A warm-up was performed to reduce the risk of injuries during rapid and maximal force production. The order of the measurements was as follows: (1) static and dynamic balance; (2) M-wave, H-reflex, and V-wave (soleus muscle); (3) maximal isometric contraction (MVC) and passive twitch torque (relaxed plantar flexor and knee extensor torque production caused by electrical stimulation); (4) MVC (knee flexor muscles); and (5) superimposed twitch (quadriceps muscle group). The time to complete the entire protocol was approximately 1.5 h.

Measurements

Body composition. Percent body fat and body mass were measured using an InBody-720 analyser (Biospace Co. Ltd., Seoul, Korea). The physical characteristics of the participants are presented in Table I.

Static balance. Static balance control was measured using balance trainer (BT4 balance platform, Hurlabs Oy, Tampere, Finland). The participants stood quietly for at least 5 s (pre-phase) before the measurement. After the pre-phase, static balance was measured during the next 5 s. Static balance was measured twice and the attempt with less average swaying in the x- and y-direction was used for analysis. Maximal anterior-posterior (y) and medial-lateral (x) centre-of-pressure swaying distance was assessed.

Dynamic balance. The prototype includes the frame of the system, pneumatic and control parts (Figure 1), and a safety frame. The system's frame is a 600×600 mm plate. The valves (Rexroth, E/P pressure regulator series ED05, Bosch Rexroth, Germany) are placed in the middle section. Supporting plates are placed in the corners, which provide appropriate stiffness to the system. Cylinders (Pimatic, P2520-40/16-125, Polarteknik PMC Oy Ab, Vantaa, Finland) are placed in each corner, 1 cm inside each edge. The area of each cylinder is 40 mm^2 and the cylinder displacement is 125 mm, which gives the plate a 12 degree dropping capacity in maximal drops. A 3 mm thick plate is placed over the cylinders. This plate is the bottom plate from a BT4 balance platform.

The system is controlled via National Instrument cards Ni cDaq-9172 and Ni 9263 (National Instruments Co., Austin, TX, USA), and the guiding software was built for Labview 7.1 (National Instruments Co., Austin, TX, USA). During the measurements, one edge of the plate was dropped at a time. A drop of 125 mm was performed during a 180 ms period. In this experiment, the edge returned to the starting position 1 s after dropping.

Dynamic balance was measured using the new dynamic balance measurement prototype. Sudden disturbance was applied to represent dynamic balance conditions. The participants stood on the balance plate for two 30 s sets, which were interrupted by four sudden balance disturbances, one in each direction (left, right, forward, backward). The participants did not know beforehand the direction and exact timing of the disturbance. During each disturbance, one side of the plate dropped 12.5 cm in free fall and stopped suddenly. The plate returned to the starting position 1 s after the disturbance. Disturbances were induced approximately every 6 s for 30 s. A black mark was placed on the wall to enable the participants to focus on a fixed point during the measurements. The dynamic 30 s set was measured twice and the attempt with less average swaying in the x- and y-direction of the centre-of-pressure was used for analysis. Because the disturbance was applied twice in the x- (left, right) and y- (backward, forward) directions, the average of the two disturbances was used to indicate each direction balance disorder. Maximal swaying distance in the medio-lateral (x) and anterior-posterior (y) stabilograms was analysed for 1 s after the disturbance with the platform remaining in the tilted position.

Maximum voluntary contraction. Knee extension and flexion MVCs were measured using a knee dynamometer (Hurlabs Oy, Tampere, Finland), with the participants seated with a hip angle of 110° and a knee angle of 120°. The participants performed three MVCs at 1 min intervals and they were instructed to perform the MVCs as fast and powerfully as possible. A force transducer was placed just above the ankle joint (knee extension) and just above the distal head of the Achilles tendon (knee flexion). Torque values were calculated by multiplying the force with the lever arm. Data were collected and analysed using an A/D converter (CED Power 1401, CED Ltd., Cambridge, UK) and Spike 5.14 software (CED Ltd., Cambridge, UK). Knee extension MVC, torque production at 200 ms and 500 ms from the onset of torque production, and knee flexion MVC were analysed. Plantar flexor MVC was measured using a custom-built force dynamometer (University of Jyväskylä, Finland). The participants sat in the dynamometer with hip, knee, and ankle angles of 110°, 180°, and 90° respectively. Participants performed five MVCs at 1 min intervals, and maximal torque was analysed. Typical examples of MVCs are shown in Figure 2.

Table I. Physical characteristics of the participants (mean $\pm s$)

Group	Age (years)	Height (m)	Weight (kg)	% Body fat
Young ($n = 10$)	27.1 ± 2.8	1.79 ± 0.08	77.1 ± 12.6	16.8 ± 4.9
Elderly ($n = 20$)	64.2 ± 2.7	1.76 ± 0.06	80.2 ± 9.1	22.0 ± 5.4
Combined ($n = 30$)	51.8 ± 17.9	1.77 ± 0.07	79.1 ± 10.3	20.3 ± 5.8

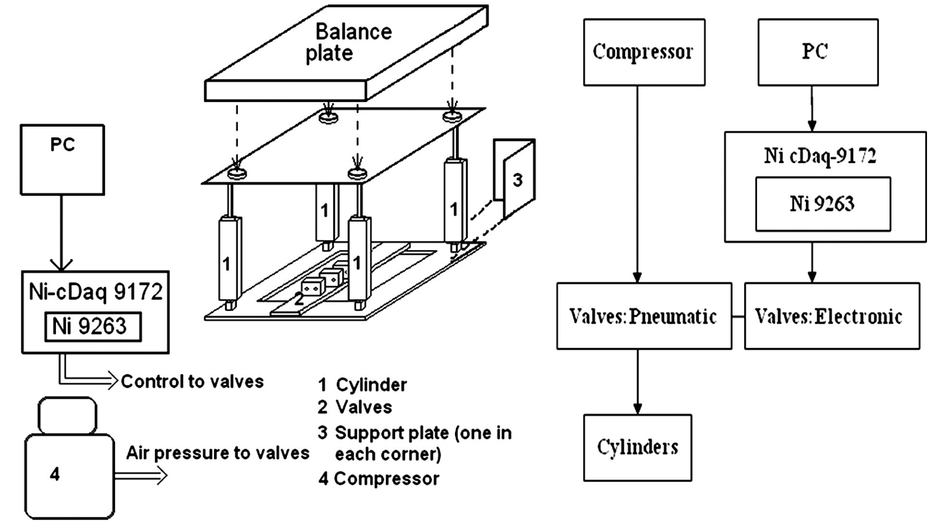

Figure 1. Dynamic balance measurement system and flow chart.

Electromyography. Bipolar electrodes were placed over five muscles (vastus lateralis, rectus femoris, biceps femoris, soleus, and medial gastrocnemius). Before electrode placement, the skin was shaved, abraded with sandpaper, and cleaned with alcohol. The impedance of the electrodes was measured, and if the resistance was higher than 10 kΩ, the preparation was repeated. Electrodes were placed according to SENIAM (Hermens et al., 1999). The data were recorded and filtered (bandwidth 10–500 Hz) using an EMG measuring system (Noraxon, Scottsdale, USA), A/D-converted (CED Ltd., Cambridge, UK), and analysed with Spike 5.14 software (CED Ltd., Cambridge, UK). During analyses, EMG data were rectified and three different time windows were used to analyse average EMG: (1) 0–200 ms; (2) 0–500 ms (knee extension and plantar flexion) from the onset of torque production; and (3) $\pm$100 ms (knee extension, knee flexion, and plantar flexion) around the peak torque value. The sum of rectus femoris and vastus lateralis aEMG in knee extension was used to calculate the $aEMG_{200ms}/aEMG_{max}$ and $aEMG_{500ms}/aEMG_{max}$ ratios. In addition, the aEMG knee extension/knee flexion ratio for the biceps femoris was calculated. These ratios were used to evaluate possible differences in the quadriceps muscle activation strategies of young and elderly males during rapid and maximal torque production, and to evaluate the amount of co-activation of the antagonist muscle. The sum of soleus and medial gastrocnemius aEMG in plantar flexion was used to the calculate $aEMG_{200ms}/aEMG_{max}$ and $aEMG_{500ms}/aEMG_{max}$ ratios to analyse different activation strategies during rapid torque production in the plantar flexors.

H-reflex and M-wave. The participants stood relaxed during H-reflex measurement. The H-reflex and M-wave responses (Figure 3) were measured in the soleus muscle by stimulating the tibialis nerve in the popliteal fossa. The correct stimulation location and the sensitivity of the H-reflex were first determined. Intensity intervals were then chosen according to the sensitivity so that H-reflex recruitment curves could be measured. During stimulation, the cathode (1.5 × 1.5 cm) was placed over the tibialis nerve and the anode (5 × 8cm) was placed superior to the patella. The stimulation used for the measurement was a rectangular pulse of 0.2 ms duration and a frequency of 0.1 Hz (DS7A, Digitimer Ltd., Welwyn Garden City, UK). The stimulation intensity began at 10 mA with 1–5 mA increments between stimulations, until maximal M-wave and H-reflex values were recorded. Alpha-motoneuron pool excitability was evaluated by calculating the maximal H-reflex/maximal M-wave ratio.

Passive twitch. Passive twitch was measured from the triceps surae and quadriceps muscle groups (Figure 3). For triceps surae measurements, the participants were seated with their foot on the force plate, and with knee and ankle angles of 180° and 90° respectively. A supramaximal (maximal M-wave + 50%) single pulse stimulation of the tibialis nerve was used to obtain a maximal muscle response. Maximal peak torque and time to peak torque were assessed. In the quadriceps muscle group, passive twitch was measured using a knee dynamometer. The participants sat with a hip angle of 110° and an ankle angle of 120°. Six stimulation electrodes (5 × 10 cm) were placed over the quadriceps muscle. Stimulation was induced using 0.2 ms double pulses with 10 ms intervals. Stimulation intensity was increased until the maximal twitch response was achieved. Maximal peak torque and time to peak torque were assessed.

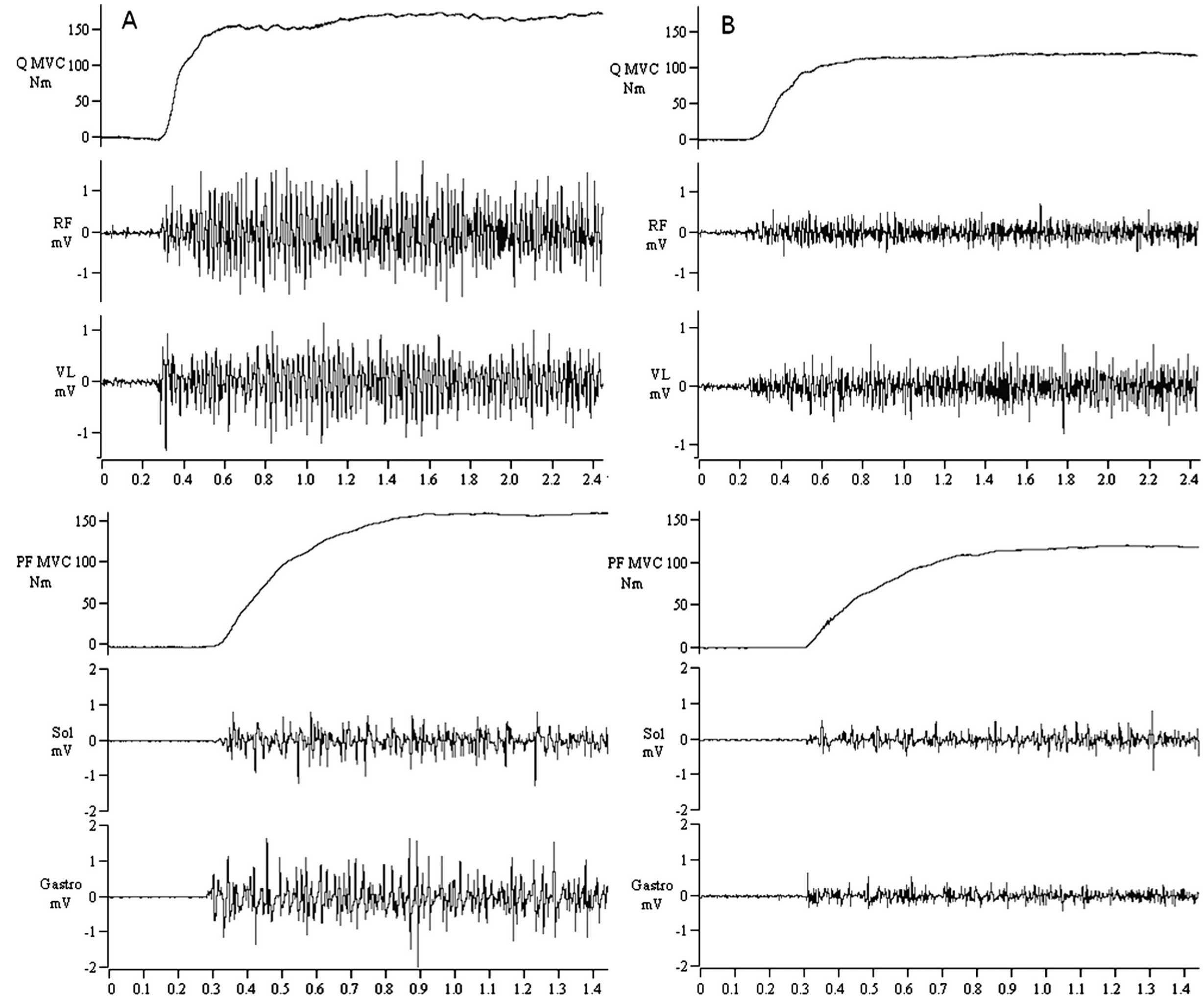

Figure 2. An example of the raw EMG and torque signals measured during maximal knee extension and plantar flexion (Q, quadriceps; PF, plantar flexor; A, young participant; B, elderly participant).

Superimposed twitch and V-wave. Superimposed twitch (Figure 3) was measured from the quadriceps muscle group (Merton, 1954). Measurements were performed during knee extension MVC with a supramaximal stimulation intensity (maximum passive twitch + 25%). Voluntary torque and superimposed stimulation torque were assessed, and activation level (AL) was calculated using the following formula (Strojnik & Komi, 1998):

$$AL = 100 - D(T_{DST}/T_{DTW})/T_{DTW} \cdot 100$$

where D is difference between the torque level before the twitch and maximal torque, T_{DST} is maximal torque after a double stimulation pulse, T_{MVC} is maximal voluntary contraction torque, and T_{DTW} is maximal passive twitch torque.

The V-wave was measured from the soleus muscle (Figure 3) in the same way as the H-reflex, but with a supramaximal stimulation intensity and during MVC. Contractions were performed with the same settings as plantar flexor MVCs. The participants performed five MVCs for 3 s each with 1 min between contractions. Peak-to-peak amplitudes of V-waves and maximal M-waves were analysed. The level of efferent neural drive from spinal alpha-motoneurons was evaluated by calculating the V/M_{max} ratio (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002) to determine possible connections between neural drive activation and balance disorders.

Statistical analyses

Mean values and standard deviations (s) were calculated. Correlations between balance parameters and neuromuscular functions were measured using Spearman's principle. Age-related differences were measured using non-parametric dependent-samples t-tests (balance) and independent samples t-tests (neuromuscular system). Spearman's rank correlation coefficient and non-parametric tests were used because the balance results were not normally

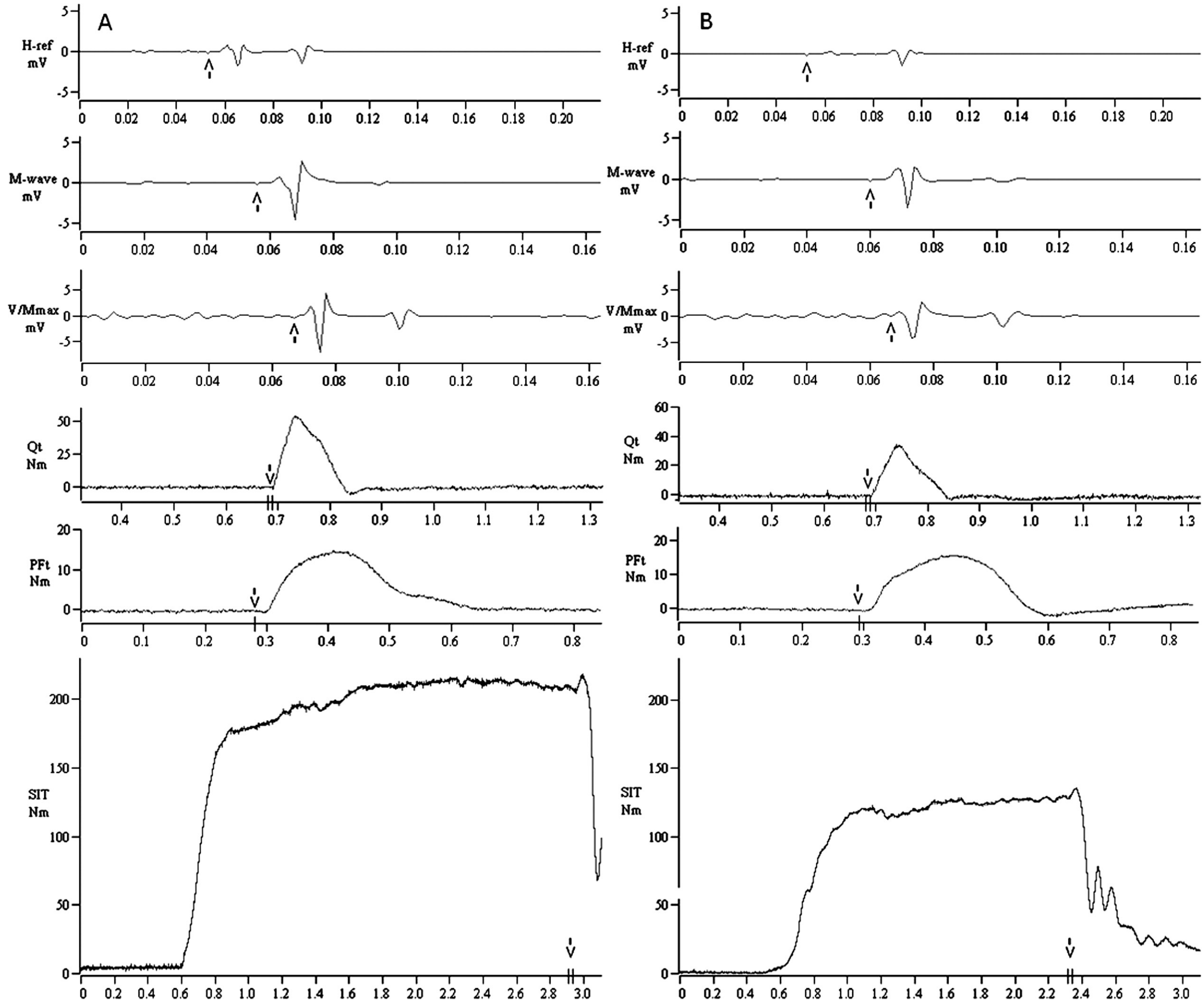

Figure 3. An example of the H-reflex, M-wave, V-wave, and passive twitch responses (quadriceps and plantar flexors) and superimposed twitch during MVC (Qt, quadriceps passive twitch; PFt, plantar flexor passive twitch; SIT, superimposed twitch test; A, young participant; B, elderly participant). Arrows show the location of the stimulation artifact.

distributed. As the results for the neuromuscular functions were normally distributed, independent samples *t*-tests were used to assess these parameters. Statistical significance was set at $P < 0.05$. The data were analysed using SPSS statistical software (version 13.0, SPSS Inc., Chicago, IL, USA).

Results

Static balance

In the static balance test, maximal swaying distance in the x- and y-directions centre-of-pressure during the 5 s period was 6.7 ± 2.4 mm and 9.5 ± 3.0 mm in the young group respectively, and 7.7 ± 2.8 mm and 13.2 ± 6.7 mm in the elderly group respectively. The relative difference in the x-direction was 15.4% between the age groups, and 38.9% in the y-direction. Results were quite similar between the age groups, so there were no significant age-dependent differences in static balance control. Maximal static swaying distance is presented in Figure 4.

Dynamic balance

In the dynamic balance test, the average swaying distance in the x-and y-directions centre-of-pressure during the 1 s period after disturbances was 87.2 ± 23.0 mm and 74.2 ± 8.1 mm in the young males respectively, and 95.5 ± 17.9 mm and 91.5 ± 19.4 mm in the elderly males respectively. The relative difference in the x-direction was 9.6% between the age groups, and 23.3% in the y-direction. As in the static test, there was no significant difference in the medial-lateral direction, but the anterior-posterior swaying distance was significantly ($P < 0.05$) higher in the elderly, indicating larger age-related differences in dynamic situations. Maximal dynamic swaying distance is presented in Figure 4. There were no significant correlations between static and

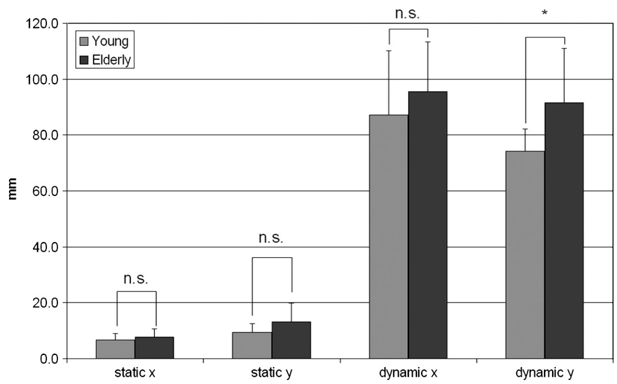

Figure 4. Balance disorder in static and dynamic balance conditions (*$P < 0.05$).

dynamic balance control in the elderly, whereas in the young static x-direction balance control correlated negatively ($r = -0.811$, $P < 0.01$) with dynamic x-direction balance, showing differences between static and dynamic balance control. To test the reliability of the dynamic balance measurement, two consecutive attempts were performed. No significant differences were observed in any of the balance variables between the two attempts.

MVC (knee extension, flexion, and plantar flexion)

Maximal isometric knee extension torque was 181 ± 42 N·m in the young and 135 ± 39 N·m in the elderly ($P < 0.01$), showing decreased maximal torque production capacity in the elderly. Similarly, during the first 200 ms, torque production was 107 ± 33 N·m in the young and 66 ± 25 N·m in the elderly ($P < 0.01$); at 500 ms, torque production was 147 ± 36 N·m in the young and 108 ± 39 N·m in the elderly ($P < 0.05$). Therefore, not only maximal force, but also rapid force production, particularly at the onset of torque production, is reduced during ageing. Results for the knee extension MVC and rapid torque production are shown in Figure 5. Plantar flexor MVC was 181 ± 15 N·m in the young and 178 ± 46 N·m in the elderly (N.S.). Plantar flexor torque production in the first 200 ms was 68 ± 16 N·m and 40 ± 15 N·m ($P < 0.01$) in the young and elderly respectively. After 500 ms, plantar flexor torque production was 114 ± 14 N·m and 100 ± 25 N·m (N.S.) in the young and old respectively, showing that there were no age-related differences in plantar flexion after that point.

There was a significant negative correlation between knee extension torque production at 500 ms and dynamic y-direction swaying for both groups combined ($r = -0.478$, $P < 0.01$) and the elderly group in isolation ($r = -0.493$, $P < 0.05$) (Figure 6); there was no such relationship in the young group. There was also a significant negative correlation between 200 ms torque production and dynamic y-direction swaying for both groups combined ($r = -0.425$, $P < 0.05$), but no such relationship was observed for either the young or elderly group in isolation.

The $aEMG_{200ms}/aEMG_{max}$ and $aEMG_{500ms}/aEMG_{max}$ ratios in quadriceps were 0.693 ± 0.228 and 0.783 ± 0.196 respectively in the young group. For the elderly, the corresponding values were 0.600 ± 0.185 (N.S.) and 0.746 ± 0.203 (N.S.) respectively, showing that there were no major differences in torque production strategies between the age groups. In addition, the aEMG knee extension/knee flexion ratio from the biceps femoris was 0.455 ± 0.306 in the young and 0.396 ± 0.322 in the elderly. No significant differences were observed between the age groups. The $aEMG_{200ms}/aEMG_{max}$ and $aEMG_{500ms}/aEMG_{max}$ ratios of the plantar flexors were 1.071 ± 0.415 and 1.014 ± 0.369 respectively in the young, and 0.776 ± 0.350 (N.S.) and 0.883 ± 0.250 (N.S.) respectively in the elderly. No significant correlations were observed between balance measurements and EMG responses. All aEMG values upon which these calculations were based are shown in Table II.

H-reflex

Average peak-to-peak amplitudes of the H-reflex were 3.13 ± 2.28 mV and 2.47 ± 1.48 mV (N.S.), and the M-wave values were 8.64 ± 2.82 mV and 7.29 ± 1.83 mV (N.S.), for the young and elderly respectively. Thus, there were no major differences in H-reflex responses and maximal muscle compound action potentials. The maximal H/M ratio, which has been used to evaluate the excitability of the alpha-motoneuron pool, was 0.368 ± 0.250 for the young and 0.344 ± 0.179 for the elderly (N.S.). Therefore, there were no major differences in spinal sensitivity. No significant correlations were observed

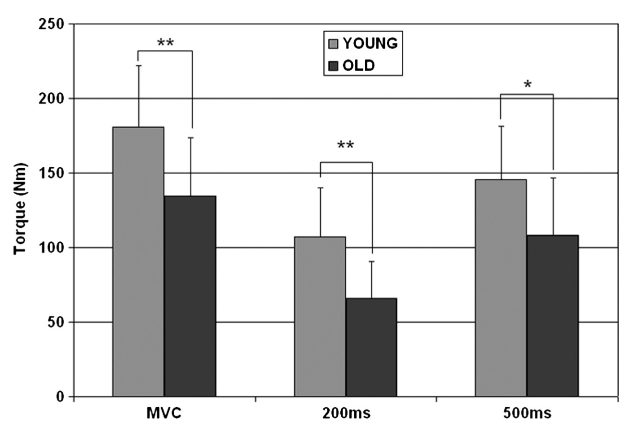

Figure 5. Knee extension MVC and rate of torque production at 200 ms and 500 ms in the young and elderly (*$P < 0.05$, **$P < 0.01$).

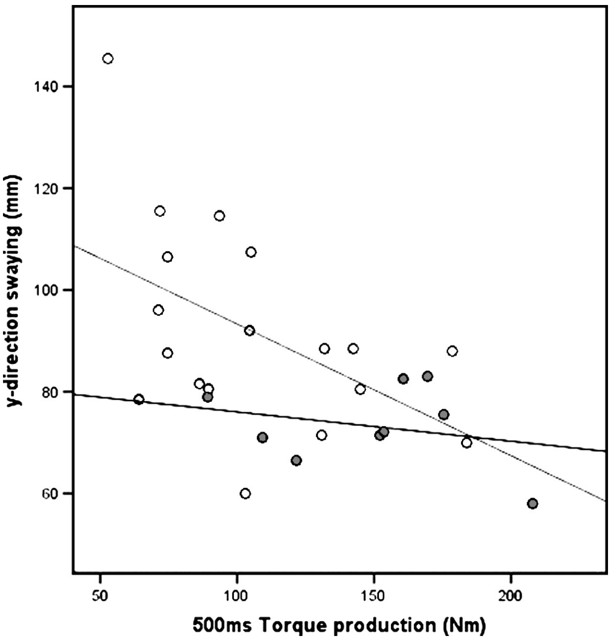

Figure 6. Relationship between dynamic balance control in the anterior-posterior direction and 500 ms knee extension torque production. ●, young participants ($n = 10$, $r = -0.262$, N.S.); ○, elderly participants ($n = 20$, $r = -0.493$, $P < 0.05$).

between reflex parameters and dynamic balance results.

Passive twitch

Passive peak twitch torque and time to peak torque for the plantar flexors were 14.2 ± 2.8 N·m and 87 ± 27 ms respectively for the young males. For the elderly, the corresponding values were 18.3 ± 5.8 N·m ($P < 0.05$) and 130 ± 17 ms ($P < 0.05$) respectively. For the quadriceps, passive peak twitch torque was 73.9 ± 8.4 N·m in the young and 47.7 ± 12.7 N·m in the elderly ($P < 0.05$). Maximal peak twitch torque was produced within 76.6 ± 8.4 ms in the young and within 69.4 ± 6.3 ms in the elderly (N.S.).

Activation level and V-wave

Activation level of the quadriceps muscle group was $96.2 \pm 0.8\%$ in the young and $93.8 \pm 2.1\%$ in the elderly ($P < 0.01$). In the young, the V-wave and M-wave peak-to-peak amplitudes were 2.94 ± 2.01 mV and 10.9 ± 2.72 mV respectively, and the V/M_{max} ratio was 0.268 ± 0.174. In the elderly, the V-wave and M-wave peak-to-peak amplitudes were 1.48 ± 0.965 mV and 7.41 ± 2.11 mV respectively, and the V/M_{max} ratio was 0.217 ± 0.164. Despite minor differences in results, no significant differences were observed between age groups.

Discussion

This study examined static and dynamic balance control and their interactions with different functions of the neuromuscular system in two age groups. The first major finding was that dynamic balance control was impaired with ageing more than static balance control. This was observed in particular in anterior-posterior swaying, which was 23.3% greater in the elderly than in the young participants. The second main finding was a clear difference in muscle group specificity between age groups. There was a significant age-dependent difference in quadriceps MVC (young: 181 N·m; elderly: 135 N·m; $P < 0.01$) and activation level (young: 96.2%; elderly: 93.8%; $P < 0.01$), whereas the differences in plantar flexion MVC, H-reflex, and V-wave activity of the soleus muscle between the two age groups were not significant.

It is known that ageing impairs balance control, and that the number of falling accidents and injuries, such as bone fractures, is thus increased (Kannus & Parkkari, 2006; Kim & Robinson, 2005). Dynamic balance is more complex to measure than static balance. Thus, one of the aims of the present study was to develop a new balance measurement system, which can cause a sudden balance disturbance. Baloh et al. (1994) showed that age-related impairment in balance control is especially evident in dynamic situations. The results of the present study show that the young participants were able to control their balance after a disturbance better than the elderly participants, especially in the anterior-posterior direction. In the static condition, differences in balance

Table II. Absolute aEMG values (μV) measured during MVC, 200 ms, and 500 ms rapid torque production (mean ± *s*)

	Biceps femoris[a]	Biceps femoris[b]	Medial gastrocnemius	Soleus	Vastus lateralis	Rectus femoris
Elderly (MVC)	40±24	110±54	220±89	190±67	245±82	158±76
Young (MVC)	62±26	160±66	371±361	184±50	299±109	229±111
Elderly (200 ms)	–	–	189±99	118±56	164±69	108±49
Young (200 ms)	–	–	308±143	178±47	217±91	147±84
Elderly (500 ms)	–	–	213±96	144±60	185±78	134±54
Young (500 ms)	–	–	280±117	185±23	238±115	180±99

[a]Activation during maximal knee extension.
[b]Activation during maximal knee flexion.

were not observed between the two age groups. This indicates that, although vertical dropping disturbance does not directly simulate natural falling conditions, there are still age-related differences between static and dynamic conditions. This suggests that the ability to re-stabilize balance after a sudden disturbance decreases with age.

It has been shown that maximal knee extension strength and rapid torque production capacity decrease during ageing (Vandervoort, 2002), which was also the case in the present study. Degeneration of high threshold motor units may decrease muscle cross-sectional area, which can be related to decreased muscle strength and power (Hakkinen & Hakkinen, 1991; Hakkinen et al., 1998). Several studies have suggested that there may be a connection between maximal strength and balance control (Izquierdo, Aguado, Gonzalez, Lopez, & Hakkinen, 1999a; Madigan, 2006). In the present study, such a relationship between maximal force production and balance control was not observed.

It is unlikely that maximal force production is needed to correct sudden balance disturbances. Instead, the ability to produce force rapidly may be more important in the prevention of falling. In this study, differences due to sudden disturbances were shown in dynamic anterior-posterior direction swaying, which was significantly correlated with 200 ms and 500 ms knee extension torque production in both groups combined. When the participants were assessed separately, anterior-posterior swaying still correlated with 500 ms torque production in the elderly but not in the young. These results emphasize the great importance of rapid torque production for gaining balance control, especially in the elderly. Despite the artificial disturbances used in the present study, this may also be of importance in preventing falling accidents. In the plantar flexors, a significant difference was observed in 200 ms rapid torque production, but not in 500 ms torque production, which also suggests muscle-group-specific degeneration in the elderly.

Changes in rapid torque production are known to be connected to changes in agonist activation (Hakkinen et al., 1998). Non-significant differences in the $aEMG_{200ms}/aEMG_{max}$ and $aEMG_{500ms}/aEMG_{max}$ ratios of the quadriceps and plantar flexors between the groups could indicate that there were no differences in agonist activation strategies. For the plantar flexors, the differences between age groups were larger than in for the quadriceps, although still non-significant. Somewhat lower plantar flexor EMG activity ($aEMG_{200ms}/aEMG_{max}$ and $aEMG_{500ms}/aEMG_{max}$ ratios) during rapid torque production in the elderly might indicate a lower amount of muscle activation in response to perturbations. Passive twitch responses from the plantar flexors also support this suggestion, showing significantly longer peak torque time in the elderly. Kim and Robinson (2005) suggested that the ankle muscles act first during balance control, leading to activation of the knee and hip muscles during more complex tasks. This might indicate that during low-amplitude perturbations, powerful and rapid force is not needed to control balance, which also explains the non-significant differences in static balance situations. Decreased agonist activation together with increased antagonist co-activation can also impair balance control, and this has been suggested to be a contributing factor to balance problems (Laughton et al., 2003). However, no differences in agonist–antagonist co-activation (extension aEMG/flexion aEMG) measured from the biceps femoris were found between groups, suggesting that this was not the case in the present study.

The results revealed large differences in passive twitch properties of the plantar flexors and quadriceps between groups. In the quadriceps, twitch torque was higher in the young participants, but the time required to achieve maximal torque was almost the same between the two groups. In the plantar flexors, peak torque was higher in the elderly, but the time to peak torque was shorter compared with the young participants. This finding suggests that ageing may have a different effect on different muscles. One explanation could be that the number of slow-twitch fibres in the plantar flexors is higher than in the quadriceps muscles (Enoka, 2001). Consequently, degeneration of high-threshold motor units may have a more pronounced effect on the torque production of the knee extensors than on the plantar flexors. Alternatively, musculo-tendinous stiffness can increase during ageing, and this could increase passive plantar flexor peak twitch torque (Ochala, Lambertz, Pousson, Goubel, & Hoecke, 2004).

In the present study, the effects of ageing were more evident in the knee extensors than the plantar flexors. An age-dependent increase in pre-synaptic inhibition is known to decrease the ability to modulate reflex output, and may influence the ability of the central nervous system to respond effectively to balance perturbations (Mynark & Koceja, 2002). Impaired postural control may also be associated with decreased proprioceptive input (Wolfson et al., 1992). Several studies have shown that H-reflex excitability decreases with ageing, although the H/M ratio does not necessarily follow the same pattern (Scaglioni et al., 2003; Vandervoort & McComas, 1986). In the present study, no significant differences in the H_{max}/M_{max} ratio were observed between the two age groups. Maximal M-wave amplitude has also been found to decrease with ageing (Scaglioni et al., 2003). The main reason for this phenomenon may be the loss of fast motor units, which can lead to reorganization of the entire neuromuscular system (Macaluso & De Vito, 2004). In the present study, no significant differences in the M-wave amplitude of the soleus muscle were observed between the young and elderly. This may be because the soleus muscle consists mainly of low-threshold muscle fibres, and thus the effects of ageing could be less pronounced. The elderly participants in the present study were physically fit and very active in their daily lives, which could also explain the small differences observed between the two groups. This was the conclusion reached by the doctor who undertook the medical examinations. Morse et al. (2004) suggested that reduced plantar flexor activation was associated with reduced physical activity. In this study, plantar flexor maximal force production was similar between the two age groups, which reflects the high physical fitness of the elderly participants. This might be one reason why there were no significant differences in static balance conditions. It has been suggested previously that level of physical fitness will influence both static and dynamic balance control (Paterson, Jones, & Rice, 2007). In addition, in the present study the elderly participants were aged between 60 and 70 years. In several previous studies, the average age was higher, and therefore the effects of ageing could have been more pronounced (Scaglioni et al., 2002, 2003).

It has been suggested that neural drive from the central nervous system changes during ageing (Izquierdo et al., 1999b). In this study, no significant differences in neural drive to the soleus muscle were observed between groups, as revealed by V-wave responses. In addition, no relationship was observed between balance control and V-wave responses. However, activation level measured from the quadriceps muscle group was significantly lower in the elderly than the young. It has been suggested previously that reduced quadriceps activation could be caused by a reduction in the number of active motor units or reduced motor unit firing rates (Sale, 2003). The lower activation level in the elderly participants might suggest that impaired neural drive leads to decreased strength and thus impaired balance control. However, we found no evidence of a relationship between activation level and dynamic balance control, suggesting that reduced neural drive may not be a limiting factor in the control of balance. Even if activation level were significantly lower in the elderly, it may still be high enough to cause appropriate activation in the muscles during different tasks. As noted earlier, rapid torque production in disturbance situations may be more important than maximal torque production. However, as suggested in this study, age-related changes may be muscle group specific. As shown, muscle activation was different in the quadriceps but not in the plantar flexors, which may indicate that central parts also have some role in balance disturbances, even if this role is less important than that of peripheral structures.

In conclusion, the present results suggest that restabilizing balance after a sudden disturbance is an age related phenomenon, and that the ageing will have more effect in dynamic than static balance control. In addition, the effects of ageing seem to be muscle group specific. Surprisingly, in both age groups central parts of the neuromuscular functions seem to play a less important role than peripheral parts in dynamic balance control.

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