TITLE

NEUROMUSCULAR MECHANICS AND HOPPING TRAINING IN ELDERLY

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Running head: Hopping training to neuromuscular function in elderly

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ABSTRACT

Purpose: The present study examined the effects of repetitive hopping training on muscle activation profiles and fascicle-tendon interaction in the elderly.

Methods: 20 physically active elderly men were randomly assigned for training (TG) and control groups (CG). TG performed supervised bilateral short contact hopping training with progressively increasing training volume. Measurements were performed before the training period (BEF) as well as after 2 weeks (2W) and 11 weeks (11W) of training. During measurements the gastrocnemius medialis –muscle (GaM) fascicle and its outer Achilles tendon length changes during hopping were examined by ultrasonography together with electromyographic (EMG) activities of calf muscles, kinematics, and kinetics.

Results: At 2W the ankle joint stiffness was increased by 21.0 ± 19.3 % and contact time decreased by 9.4 ± 7.8 % in TG. Thereafter, from 2-11W the jumping height increased 56.2 ± 18.1 % in TG. Simultaneously tendon forces increased 24.3 ± 19.0 % but tendon stiffness did not change. GaM fascicles shifted to shorter operating lengths after training without any changes in their length modifications during the contact phase of hopping. Normalized EMG amplitudes during hopping did not change with training.

Conclusions: The present study shows that 11 weeks of hopping training improves the performance of physically active elderly men. This improvement is achieved with shorter GaM operating lengths and therefore increased fascicle stiffness and improved tendon utilization after training. Based on these results hopping training could be recommended for healthy fit elderly to retain and improve rapid force production capacity.

Keywords: stretch-shortening cycle; aging; ultrasound; electromyography; tendon; gastrocnemius medialis

ABBREVIATIONS

AJS	Ankle joint stiffness
ATF	Achilles tendon force
BEF	Baseline (first) measurement session before training
CG	Control group
EMG	Electromyography
Fz	Vertical component of the ground reaction force
GaL	Gastrocnemius lateralis muscle
GaM	Gastrocnemius medialis muscle
GRF	Ground reaction force
KJS	Knee joint stiffness
MTU	Muscle-tendon unit
MTJ	Muscle-tendon junction
MVC	Maximal voluntary contraction
RMS	Root mean square
RSI	Reactive strength index
SOL	Soleus muscle
TA	Tibialis anterior muscle
TG	Training group
2W	Second measurement session after 2 weeks of training
11W	Third and last measurement session after 11 weeks of training

INTRODUCTION

When elderly people are compared with younger ones, they reportedly have different agonist and antagonist muscle activation profiles during dynamic movements (Hoffren et al. 2007; Hoffren et al. 2011; Hortobagyi and DeVita. 2000; Häkkinen et al. 1998). This age-related behavior may also be demonstrated in the adaptation of the muscle fascicle–tendon interaction in normal activities such as in walking (Mian et al. 2007; Panizzolo et al. 2013) and hopping in place (Hoffren et al. 2007; Hoffren et al. 2012), which are basic examples of the stretch-shortening cycle way of muscle function. Generally, the movements in elderly can be characterized as weak (Candow and Chilibeck. 2005; Norris et al. 2007), slow (Lanza et al. 2003; Norris et al. 2007) and less economical (Malatesta et al. 2003; Mian et al. 2006) when compared to those of the young. Part of these changes are due to the aging process itself (Pearson et al. 2002) but may be partly explained by the decrease in physical activity level that typically occurs with aging (Hunter et al. 2000), especially high intensity exercises that require rapid force production (Candow and Chilibeck 2005; Morse et al. 2004).

However, in order to be able to function independently and avoid falls, the elderly also should have a reserve for rapid force production, for example, in situations when balance needs to be corrected quickly after tripping. Ankle joint functional capacity (high rate of development in muscle activation and high plantarflexor moment) is important in regaining balance after tripping (Pijnappels et al. 2005a; Pijnappels et al. 2005b) and has been reported to have decreased in elderly fallers compared to non-fallers (LaRoche et al. 2010). In addition, ankle joint functional capacity is the weakest link in elderly during walking (Beijersbergen et al. 2013; Clark et al. 2013), which is a prerequisite for independent living and the most common form of physical activity among elderly. It thus appears that training of muscles that actuate the ankle joint could be expected to have functional relevance in the elderly.

It is currently unclear whether the activation patterns and fascicle and tendon function during dynamic movements could be modified among elderly by an appropriate exercise regime to resemble those of young individuals. It is well established that strength training improves maximal force and power in elderly and young adults alike (Newton et al. 2002, Reeves et al. 2003) and that during the early phase of training, the improvements in performance are due to neural adaptations (Hakkinen and Komi 1983). Therefore, it could be speculated that the elderly could change their muscle activation profiles with short term explosive type training. If training increases the agonist activation and / or decreases antagonist coactivation during the early part of contact (braking phase) in elderly, it would increase hopping efficiency (Bosco et al. 1982; Finni et al. 2001; Kuitunen et al. 2007; Kyrolainen et al. 1998) and leg / joint stiffness (Hoffren et al. 2007; Hoffren et al. 2011; Kuitunen et al. 2007; Yoon et al. 2007). At longer term, cyclic training that includes high-strains has been shown to change the tendon mechanical properties so that tendon stiffness has increased in young individuals (Arampatzis et al. 2007), but the effects of longer-term high strain cyclic training has not been investigated in the elderly. If training increases tendon stiffness in elderly, it would counteract the effects of aging. That is because tendon stiffness decreases with aging (Karamanidis and Arampatzis. 2005; Kubo et al. 2003; Morse et al. 2005). It is currently unclear to what extent potential training-induced changes in muscle activation profiles and tendon mechanical properties would affect the fascicle-tendon interaction and performance of elderly individuals during dynamic movement. In practical terms improvements in the rate of force development and balance control could positively affect the ability of an elderly individual to recover from a perturbation.

Consequently, the purpose of the present study was to examine the effects of short and longer term repetitive hopping training on muscle activation profiles and fascicle-tendon interaction in physically active elderly men. It was hypothesized that short term training in elderly men would lead to modulation of their muscle activation profiles (increased EMG ratio of braking phase activation to push-off phase activation) to more closely resemble those of young individuals. Our second hypothesis was that longer term hopping training would result in increased tendon stiffness in the elderly.

METHODS

Subjects

In total, 24 elderly subjects volunteered for the study. Twelve of them were randomly assigned to the training group (TG) and 12 to the control group (CG). The present report is part of a larger study that also examined the effects of hopping training on bone biomarker response and these results have been reported elsewhere (Rantalainen et al. 2011). Randomizing was performed with concealed envelopes executed by drawing lots blindly. Two trained subjects dropped out due to injury. One of them injured his leg outside of the training sessions and the other developed pain in the Achilles tendon possibly due to training (Achilles tendon tendinitis). One control subject dropped out because of illness and one did not perform the maximal hopping test of the last measurements because of a leg injury that was not related to measurements. Therefore 10 trained and 10 control subjects participated all of the measurements. Both groups were physically active. The volumes of physical activity did not differ between the groups (table 1). Before measurements the subjects were given an informed consent of the procedures and risks associated with the study and they gave their written consent to participate. Medical screening was performed for all subjects before the first measurements. Exclusion criteria included coronary artery disease, neurological diseases and current lower extremity and low back pain as well as previous injuries in the leg joints. The recommendations contained in the Declaration of Helsinki were followed and the study was approved by the local ethics committee.

Protocol for the measurements

Both groups participated in three measurement sessions: before training (BEF), after 2 weeks (2W), and after 11 weeks (11W). The subjects performed repetitive two-legged hopping on a piezoelectric force platform (Kistler® model 9281B, Kistler Instrumente AG, Winterthur, Switzerland, natural frequency ∼600 Hz, Kistler amplifier model 9861A). A maximal rebound test was performed at first (PRE100%). Individual determination of the submaximal hopping intensities (50% and 75%) was based on peak vertical ground reaction force (Fz) of this PRE100% hopping test. The hopping duration at each intensity level was 10 seconds. This resulted in 15 to 20 repeatable hops. In submaximal hopping the subjects received visual feedback about their Fz levels from the monitor in front of them. Maximal hopping was measured also at the end of the protocol (POST100%) in order to examine the learning effect within the measurement session. However, the PRE100% and POST100% hopping tests did not differ significantly at BEF with regard to jumping height and contact time (Hoffren et al. 2011). Therefore, only results from the POST100% hopping test are presented for the parameters of the present study and for simplicity POST100% is referred as 100% hopping intensity in the Results and Discussion sections. In each hopping series, the subjects were asked to achieve the required hopping intensity with approximately five hops and then to maintain the required level for at least another five hops. The instruction was to jump with short contact time and with as little knee bending as possible. Before the actual measurements, the subjects performed a standardized warm-up with 10 minutes of cycling on a bicycle ergometer with a freely chosen cadence and resistance followed by balance board exercises for three times 20 seconds and 10 heel raises on the edge of a stair. In addition, the subjects were allowed to familiarize themselves for jumping by performing a few submaximal jumping series on the force plate. Immediately before the jumping measurements, the relaxed upright standing position of 10 seconds in duration was recorded to serve as a control series for ultrasound analysis. In order to record maximal muscle activation to normalize electromyographic (EMG) activities during hopping, maximal voluntary isometric plantarflexion and dorsiflexion contractions (MVC) were measured. During these measurements subjects lay prone on a measurement table with straight knees (180 deg) and the ankle joint of the right leg fixed at a 90 degree position and with hands gripping the sides of the table in order to restrict their bodies from moving. Then they either pushed (plantarflexion) or pulled (dorsiflexion) maximally against the strain gauge attached to their ball of the foot and held the force steady for at least for a few seconds.

Hopping training

TG performed 11 weeks of supervised training three times per week, on Monday, Wednesday, and Friday in an exercise laboratory. Training included the same standardized warm-up previously described. This was followed by repetitive series of submaximal bilateral hopping on the ball parts of the feet (hopping series) on a force platform. Maximal hopping was measured every 2 weeks for proper readjustment of submaximal intensity levels. One hopping series lasted for 10 seconds followed by intermediate resting periods of 1-5 min until the subjects' heart rate recovered to resting values. During hopping subjects got continuous visual feedback about their F_z levels from a monitor in front of them. On week 1, the subjects performed 4 hopping series with 75% intensity from peak F_z of PRE100% hopping test measured at BEF. Training volume was increased progressively by increasing the number of hopping series as well as the intensity (table 2). CG did not participate in the training sessions and was asked to continue their normal daily routines.

Data recordings

During hopping, the ground reaction force components (F_z, F_y, F_x) were stored in a personal computer through an AD converter (Sampling rate 1 kHz; Power 1401, Cambridge Electronics Design Ltd, England). All jumps were video-recorded at 200 fps (Peak Performance Inc, USA) from the right side perpendicular to the line of motion. Reflective markers were placed on trochanter major, the approximate centre of rotation of the knee, lateral malleolus, lateral side of the heel, fifth metatarsal head, behind the foot on top of the calcaneus and on the calf under the ultrasound probes.

EMG activity was recorded from the soleus (SOL), gastrocnemius medialis (GaM), gastrocnemius lateralis (GaL) and tibialis anterior (TA) muscles of the right leg. These recordings were stored simultaneously with 3D reaction forces (F_z, F_y, F_x) to a personal computer through an AD converter (Power 1401, Cambridge Electronics Design Ltd, England) with a sampling frequency of 1 kHz. Bipolar miniature size surface electrodes (Blue Sensor N-00-S/25, diameter 6 mm; interelectrode distance 20 mm, Medicotest A/S, Olstykke, Denmark) were used for EMG recording (Glonner electronic, Munich, Germany; input impedance >25 MΩ, common mode rejection ratio >90 dB). Before electrode placement, the skin was shaved, abraded, and cleaned with alcohol in order to secure an inter-electrode resistance value below 5 kΩ. The electrode placement followed the SENIAM guidelines (Hermens et al. 1999) as accurately as possible.

Longitudinal images of the right leg GaM muscle-tendon junction were recorded during hopping using B-mode ultrasonography (SSD-5500; Aloka, Japan) with a 6 cm linear array probe (scanning frequency of 7.5 MHz). The recordings were obtained at 96 images s^{-1}. Simultaneously, longitudinal images of GaM muscle fascicles of the right leg were recorded using another B-mode ultrasonography (α10; Aloka, Japan) with 4 cm linear array probe (scanning frequency of 13 MHz). These images were obtained at 204 images s^{-1}. The two probes were fixed securely with a special support device made of polystyrene. The superficial and deep aponeuroses and GaM fascicle as well as GaM mucle-tendon junction were digitized and tracked from each image.

An electronic pulse was used to synchronize the kinetic, kinematic and ultrasonographic data.

Data analyses

The points of reflective markers were digitized automatically and filtered with a Butterworth fourth-order filter (cut-off frequency 10Hz) using Motus software (Peak Performance Inc, USA) in order to calculate knee and ankle joint angles and then GaM muscle-tendon unit (MTU) length changes.

EMG-signals were first band-pass filtered (10–500 Hz), full-wave rectified and then low-pass filtered at 75 Hz (Butterworth type 4th-order digital filter) in order to examine the EMG profiles. After these processes, the root-mean-square values (RMS) were calculated for the following three phases; preactivation, braking, and subsequent push-off phases. The preactivation phase was defined as the 100 ms period preceding the ground contact (Komi et al. 1987). The transition from the braking to the push-off phase was marked, when the ankle joint angle was at its minimum (dorsiflexion). In general, four to five hops were averaged for each subject per intensity. The criteria for choosing the hops were as follows: 1) the force level matched the required intensity, 2) balance during hopping was maintained (stable force-time curves) and 3) the signals were free from noise.

In order to compare the EMG profiles over training groups and measurement time points, the EMG ratio of braking phase RMS over push-off phase RMS was calculated for agonist muscles. High braking over push-off phase EMG ratio resembles efficient jumping performance (Aura & Komi 1986, Kyröläinen et al. 1998). In addition, in order to compare EMG activities over training groups and measurement time points in different functional phases of hopping, RMS values during different functional phases were normalized to RMS activation during isometric MVCs. When doing that the RMS activations of plantarflexor muscles (SOL, GaM and GaL) during isometric plantarflexion MVC was used to normalize the EMGs of those muscles during hopping. Similarly, the RMS activation of TA during isometric dorsiflexion MVC was used to normalize TA EMG during hopping. TA muscle serves as an antagonist to plantarflexors during the braking phase of hopping. Coactivation indexes of different muscle pairs (TA/SOL, TA/GaM and TA/GaL) during the braking phase were calculated as follows:

$$\text{Coactivation index} = \frac{\text{Normalized TA RMS during the braking phase}}{\text{Normalized SOL, GaM or GaL RMS during the braking phase}}$$

The model of Hawkins & Hull (Hawkins and Hull 1990) was used to calculate GaM MTU length changes. Digitized GaM muscle-tendon junction data was interpolated to 200 Hz to match the time scale of the kinematic data. The following equation was used to determine the GaM outer tendon length (L_{tendon}) changes during hopping (Hoffren et al. 2012):

$$L_{tendon} = (X_{hopping} - X_{standing}) + (Y_{hopping} - Y_{standing}) + Z_{standing}, \text{ where}$$

X = Achilles tendon segment length marked with reflective markers on calcaneus and under the ultrasound probes and analyzed from the kinematic data

Y = GaM muscle-tendon junction (MTJ) length analyzed from ultrasound data

Z = GaM tendon length from calcaneus to MTJ measured with measuring tape during standing before any measurement devices were attached to skin. The position of MTJ was determined with ultrasonography.

For simplicity, GaM outer tendon length is referred to as tendon length in the results section. It must be noted that the straight tendon model used in this study does not take into account the tendon curvature and therefore the results concerning tendon length may be slightly underestimated and tendon elongation and strain overestimated when compared to the curved tendon model (Stosic and Finni 2011). MTU and tendon stretching amplitudes during the braking phase were calculated from the length during contact instant to the peak length and shortening amplitudes in the push-off phase from peak length to length at take-off instant.

GaM fascicle length was defined as the length of the fascicle line between the superficial and deep aponeuroses and pennation angle as the angle of the fascicle line and the deep aponeurosis. Fascicle length was analyzed along its path with three points: insertion to deep and superficial aponeuroses and one point in between them in order to take into account the fascicle curvature

visible in some subjects. When fascicle length exceeded the analyzing window, a linear extrapolation of the superficial aponeurosis and fascicle line was performed in order to determine the fascicle insertion to the superficial aponeurosis and therefore the fascicle length. The fascicle lengths were digitized by two people so that both of them had equal number of subjects from TG and CG and the same person digitized all the hopping series from one individual. Intra-class correlation coefficients (ICC) and 95% confidence intervals (CI) were calculated for fascicle lengths measured at resting condition as well as at various points of 100% hopping for CG (n=10) between BEF and 2W. The values were the following: fascicle length measured at resting condition ICC of 0.831 (95% CI of 0.457-0.955), at contact instant of 100% hopping ICC of 0.735 (95% CI of 0.239-0.937), at transition point from braking to push-off phase ICC of 0.820 (95% CI of 0.431-0.952) and at the take-off instant ICC of 0.876 (95% CI of 0.579-0.968). Fascicle length change amplitude during the braking phase was calculated from the length at contact instant to the length at the transition point from braking to push-off phase and the amplitude during the push-off phase from the length at the transition point to length at take-off. MTU and tendon stretching amplitudes were calculated from length during contact instant to peak length and shortening amplitudes from peak length to length at take-off instant.

Ankle and knee joint moments were calculated with inverse dynamics (Winter. 1990). Masses of the foot and shank segments as well as the locations of centers of mass and radius of gyrations of the segments were determined from anthropometric data according to Dempster (Winter. 1990). The quotient of change in ankle or knee joint moment generated by the right leg (from contact to peak) divided by change in ankle or knee joint angle (from contact to min) (Kuitunen et al. 2002) was used as a value of ankle joint stiffness (AJS) and knee joint stiffness (KJS), respectively, during the braking phase.

Achilles tendon forces (ATF) of the right leg were estimated by dividing the ankle joint moment over the Achilles tendon moment arm. Moment arm values were based on literature (Rugg et al. 1990) and the calculation took into account the change in moment arm length due to the change in ankle joint angle. Average tendon stiffness during the braking phase of hopping was calculated by dividing the peak ATF over the GaM tendon stretch from contact to peak length. The reactive strength index (RSI) was calculated as flight time divided by contact time (Flanagan et al. 2008).

Statistics

The results are presented as means and standard deviations (SD). Differences in background information between the groups were tested using Student's t-test for independent samples. Normality of the parameters was tested using the Shapiro-Wilk test and equality of variances with Levene's test. If either of these tests failed, the non-parametric Kruskal–Wallis test was used to examine differences between TG and CG. The ANOVA for repeated measurements on two factors was used to test the main effects of training period (BEF, 2W, 11W) and group (TG, CG) as well as the interactions on different parameters. The ANOVA for repeated measurements on one factor and post hoc Bonferroni were used to determine the significant differences between measurement time points (BEF, 2W, 11W) separately for TG and CG. In addition, the difference between TG and CG in specific hopping intensity and measurement time point was tested with Student's t-test for independent samples. The same procedures with normality and homogeneity of variance were followed as with background information parameters. Relationships between variables were investigated using Pearson's product-moment correlation coefficient. The level of statistical significance was set at $p < 0.05$.

RESULTS

Background information

There were no differences in age, height, weight, body mass index, exercise times, or exercise hours between TG and CG (table 1).

TRAINING OUTPUT AT 100% HOPPING INTENSITY

Kinematics

At BEF there were no differences in knee and ankle joint angles at contact and take-off instants or at minimum joint angles during hopping between TG and CG. Training induced only minor changes to kinematics (figure 1).

Knee and ankle joint angle amplitudes during the braking and push-off phases did not differ at BEF between TG and CG. Knee and ankle joint angle amplitudes from contact instant to minimum angle decreased in TG from BEF-2W (both $p<0.05$). Ankle joint angle amplitude in TG decreased also during the push-off phase (from minimum angle to angle at take-off instantt) from BEF-2W ($p<0.01$) whereas no changes were observed at knee joint angle amplitude.

Jumping height

At BEF there were no differences in jumping height at 100% between TG and CG (4.9 ±3.1 cm vs. 6.7 ± 1.7 cm, respectively). There was significant interaction between study group (TG or CG) * jumping height from 2-11W ($p<0.05$) with opposite (but ns) trends of decrease and increase in jumping height in TG and CG, respectively. Therefore, at 2W CG jumped higher than TG (7.2 ± 1.6 cm vs. 3.9 ± 3.1 cm, respectively, $p<0.01$). Jumping height increased significantly in TG from 2-11W (56.2 ± 18.1 %, $p<0.01$) and did not change in CG (figure 2A).

Contact times

At BEF there were no differences in total contact time at 100% between TG and CG (272 ± 32 ms vs. 241 ± 35ms, respectively). In TG, contact time shortened from BEF-2W ($p<0.05$) (figure 2B). Thereafter, significant study group * contact time interaction existed from 2-11W ($p<0.05$) when the BEF contact time was used as a covariate with opposite (but ns) trends of decrease and increase in contact time in TG and CG, respectively.

Braking phase time at 100% did not differ between TG and CG at BEF (123 ± 21 ms vs. 112 ± 12 ms in TG and CG, respectively) or in any other measurement points. In addition, the braking phase time did not change in either group with training. Push-off phase time at BEF (148 ± 17 ms vs. 129 ± 24 ms in TG and CG, respectively) did not differ between the groups either. However, push-off phase time shortened in TG from BEF-2W ($p<0.05$). Thereafter, significant study group * push-off phase time interaction existed from 2-11W ($p<0.05$) with opposite (but ns) trends of decrease and increase in push-off phase time in TG and CG, respectively.

Reactive strength index (RSI)

At BEF CG had higher RSI than TG at 75% ($p<0.05$). RSI increased in TG from BEF-11W at 75% and 100% on average 62.5 ± 72.9 % (in CG 19.8 ± 42.4 %) and from 2-11W 55.3 ± 64.2 % (in CG 9.8 ± 31.3 %) (figure 3). In addition, significant training group * RSI interactions were observed from 2-11W at 50% ($p<0.05$) and 75% ($p<0.01$).

Peak Fz

At BEF peak Fz at 100% did not differ between TG and CG. Peak Fz increased in TG from BEF-11W (p<0.05) and from 2-11W (p<0.01) but did not change in CG (figure 2C). Significant study group * peak Fz interaction existed from 2-11W (p<0.05): Peak Fz increased in TG (p<0.01) and did not change in CG.

Joint stiffness

At BEF AJS and KJS during the braking phase of hopping did not differ between TG and CG at any intensity level. AJS increased at 100% from BEF-2W (p<0.05) and BEF-11W (p<0.01) in TG and did not change in CG (figure 2D). There were no training effects in AJS in submaximal level. Training did not have any effect on KJS values.

EMG ACTIVATION

When normalized EMG activities in different functional phases were compared between TG and CG, CG showed higher values at BEF in GaM pre- and braking phase activations at 75% and 100% (all p<0.05). Thereafter, at 11W TG had lower normalized TA activation in the braking phase at 100% as compared to CG (p<0.05). Other than these, no between groups differences existed. In addition, no within group changes or interactions due to training were found in normalized EMG activations.

Braking over push-off phase EMG ratios of plantarflexors did not differ between TG and CG at BEF. EMG ratios increased in TG from BEF-2W at 100% (SOL and GaM p<0.01, GaL p<0.05). For simplicity, these changes are presented in figure 4 only for GaM muscle. However, the EMG ratio decreased again in TG at 100% from 2-11W in GaM (p<0.05) and in SOL and GaL the trends were similar (SOL p=0.084 and GaL p=0.111, ns).

Coactivation

At BEF, as compared to CG, TG had higher TA/SOL and TA/GaM coactivation indexes during the braking phase of hopping at 50% (TA/SOL 17.4 ± 9.6 % vs. 8.7 ± 6.2 % and TA/GaM 19.1 ± 13.1 % vs. 8.4 ± 5.3 % in TG and CG, respectively, both p<0.05). Thereafter, significant training group * coactivation interactions were observed at TA/SOL and TA/GaL coactivations from 2-11W at 50% (both p<0.05): opposite (but ns) trends of decrease and increase in coactivation in TG and CG, respectively, although no within group changes were found in any intensity level when groups were examined independently.

GaM MECHANICAL BEHAVIOR

The average length change patterns of GaM muscle muscle-tendon unit (MTU), outer tendon and fascicle are presented in figure 5 separately for TG and CG at all measured time points and intensities. MTU and tendon length showed stretching followed by a shortening pattern whereas fascicle length did not change greatly during contact phase. The significant changes between TG and CG at different levels are presented in the paragraphs below.

Peak Achilles tendon force (ATF)

At BEF there were no differences in peak ATF values at 100% between TG and CG (2429.0 ± 531.3 N vs. 2864.3 ± 598.9 N, respectively). However, as compared to CG, TG had lower ATF values at 2W (p<0.05). Thereafter, peak ATF increased 24.3 ± 19.0 % in TG from 2-11W (p<0.01).

MTU length

At BEF there were no differences in GaM MTU lengths or amplitudes during hopping between TG and CG except that shortening amplitude in push-off phase was higher in CG as compared to TG at 75%. Training caused some changes to MTU

function. The general trend in TG was that MTU stretching and shortening amplitudes first decreased from BEF-2W and then increased over the BEF level from 2-11W (figure 6A). Significant MTU shortening amplitude * training group interaction was observed at 75% from 2-11W ($p<0.05$).

Tendon length

GaM outer tendon lengths during relaxed upright standing position at BEF were 20.2 ± 3.0 cm vs 19.2 ± 2.1 cm in TG and CG, respectively, with no significant difference between groups. Training did not have any effect on tendon resting lengths.

At BEF there were no differences in GaM tendon stretching and shortening amplitudes between TG and CG. Following the change in MTU level, tendon stretching and shortening amplitudes increased from 2-11W in TG (figure 6B).

At BEF, the GaM tendon stretch relative to MTU stretch at 100% hopping was 56.1 ± 17.0 % vs. 62.9 ± 14.9 % in TG and CG, respectively, with no significant difference between the groups. The ratio did not change with training. At BEF the tendon shortening accounted on average for 44.3 ± 25.8 % vs. 60.7 ± 11.7 % of MTU shortening at 100% in TG and CG, respectively, with no significant difference between the groups. However, at 11W the tendon / MTU shortening at100% was higher in TG (58.3 ± 10.7 %) than in CG (46.7 ± 12.9 %) ($p<0.05$).

Tendon strain (relative to length during relaxed standing) during the braking phase of 100% hopping was at BEF 6.3 ± 2.5 % in TG and. 8.3 ± 2.5 % in CG with no significant difference between the groups and it did not change with training.

Tendon stiffness

At BEF the average GaM tendon stiffness during the braking phase of hopping was at 100% 210 ± 81 N / mm in TG and 190 ± 88 N / mm in CG with no significant change with training. Average tendon stiffness did not change with change in hopping intensity either.

Fascicle length

At BEF GaM fascicle lengths during the relaxed upright standing position were 5.1 ± 1.1 cm and 5.8 ± 0.7 cm in TG and CG, respectively, with no significant differences between the groups. The pennation angles were also similar with 19.6 ± 4.5 deg and 19.5 ± 2.0 deg in TG and CG, respectively. Training did not have an effect on these resting fascicle lengths and pennation angles.

When fascicle lengths were compared between contact instant, transition point from braking to push-off phase, and take-off instant, the only significant findings were observed in TG at 11W where the fascicles shortened in TG from transition point to take-off instant at 75% and 100% (both $p<0.05$). Other than that, the fascicles behaved isometrically during hopping in TG and CG.

At BEF, the fascicle lengths at contact instant, at transition point from braking to push-off phase and at take-off instant did not differ between TG and CG. Training had only a minor effect on fascicle behavior except for the shift of the fascicles to lower lengths at 11W in TG (figure 5). GaM fascicles were shorter in TG as compared to CG at 11W at contact instant, at transition point from braking to push-off phase as well as at take-off instant at 50% and 75% (all $p<0.05$). Except for an obvious shift of fascicles to a shorter length at 11W, there were no differences in fascicle length change amplitudes during the braking or push-off phases between TG and CG at any intensity level or measurement point. In addition, the length change amplitudes did not change with training in either group.

Correlations between hopping performance and muscle mechanical behavior

Correlations between the jumping height at 100% at 11W and selected muscle mechanical behavior parameters are presented in table 3. Those trained subjects that jumped the best at 11W had high ATF and MTU and tendon stretching and shortening amplitudes during hopping. In addition, their GaM fascicles did not shorten much in the push-off phase. These correlations were not found in CG.

Finally, those trained subjects that increased their jumping height the most from 2-11W had the highest increase in GaM MTU stretch (r=0.67, p<0.05, n=10) and tendon strain (r=0.79, p<0.01, n=10). Again these correlations were not found in CG.

DISCUSSION

This study measured the effects of shorter and longer term hopping training on muscle activation profiles and fascicle-tendon interaction in the elderly. The main findings of the study were that 1) hopping training was effective in improving the jumping height and reactive strength index in elderly from 2-11W, 2) GaM fascicles shifted to a shorter operating length after training with unchanged fascicle length change patterns during the contact phase of hopping and 3) increased tendon utilization was observed after training that was an important contributor to improved jumping height.

First of all, with two weeks of hopping training the elderly learned to concentrate on the use of ankle joints during hopping, which resulted in stiffer performance with increased AJS, shorter contact times, and decreased ankle and knee joint angle amplitudes during the braking phase. Due to that, there was a tendency for jumping height to decrease in TG from BEF-2W. This seems logical since the instruction was to jump with short contact time and as little knee bending as possible. Thereafter, with longer term training the contact time remained at a low level but jumping height and RSI increased in TG. The training effect in these parameters is similar to Taube et al. (2012) in young subjects with 4 weeks of drop jump training from 30cm dropping height except that only a trend for increased jumping height was observed in Taube et al. (2012) and a significant increase from 2-11W was observed at present study. This seems logical because of considerably shorter training period in Taube et al. 2012 as compared to present study.

In previous studies, the elderly when compared to the young have been shown to have lower AJS during the braking phase of hopping in high hopping intensities, lower braking over push-off phase EMG ratios in drop jumps and hopping due to less agonist activation in the braking phase and therefore less fascicle shortening (Hoffren et al. 2007; Hoffren et al. 2011; Hoffren et al. 2012). Since the elderly do not regularly perform this kind of exercise, it was important to be able to confirm that these differences are not due to unfamiliar exercise. The present study shows that with short term training the AJS during maximal hopping increased in TG from 5.0 ± 1.4 Nm/deg at BEF to 6.1 ± 2.1 Nm/deg at 2W. We compared this to our data from young individuals (7.6 ± 1.9 Nm/deg) and did not find a statistical significance (p=0.14, ns) anymore, although the values are still a bit lower in the elderly when compared to the young. Therefore, it may be that lower AJS values in the elderly in previous studies are because of safety strategy to reduce the impact loads or inability to load ankle joints due to unfamiliar exercise and thus is not actually an age-related phenomenon. However, the fascicle function during hopping was unchanged with training and therefore the clear age-related difference in fascicle behavior (Hoffren et al. 2007; Hoffren et al. 2012) exists during hopping even after elderly have trained.

Some researchers have suggested that the increase in jumping height after plyometric training in young individuals is due to enhanced neural control during hopping (Chimera et al. 2004; Taube et al. 2012; Van Cutsem et al. 1998). Since we have also reported lower EMG ratios of braking over push-off phase RMS during hopping in the elderly when compared to the young

(Hoffren et al. 2007; Hoffren et al. 2011) and since high EMG ratio is a characteristic of efficient hopping performance (Bosco et al. 1982; Finni et al. 2001; Kuitunen et al. 2007; Kyrolainen et al. 1998), it was hypothesized that with hopping training the EMG ratios would increase in the elderly to resemble a profile closer to that of the young. Indeed, the results supported our hypotheses since EMG ratios of SOL, GaM and GaL increased from BEF-2W at 100% intensity. However, although we found an increase in jumping height from 2-11W in TG, the EMG ratios returned to BEF levels between these time points. Therefore, it seems that this EMG profile is more natural / optimal for the elderly during hopping and age-related muscle activation profiles (Hoffrén et al. 2007 and 2011) exist even when the elderly have trained, at least in the time frame of 11 weeks. It is likely that the age-related motor unit remodeling (for review see Andersen. 2003) and changed tendon mechanical properties (Karamanidis and Arampatzis. 2005; Kubo et al. 2003; Morse et al. 2005) favor different kinds of muscle activation for optimal efficiency and power output in these two age groups (Lichtwark and Wilson. 2005b). To support the findings of Kubo et al. (2007) and Kyröläinen et al. (2004) and (2005) that also reported unchanged muscle activation after plyometric training, the present study suggests that the increase in jumping height with 11 weeks of hopping training in the elderly was not caused by increased neural control of muscles because no training induced changes in normalized EMG values were observed.

With training, the GaM fascicle length change pattern during the contact phase of hopping was unchanged but instead the whole fascicle shifted to shorter position (figure 5). This decrease in fascicle operating length cannot be explained by increased neural command since no changes in GaM preactivation due to training was observed. However, shorter fascicle position but unchanged length change pattern together with increased tendon forces suggest that fascicle stiffness increased after training since fascicles were not stretched under the increased force. No changes were observed in muscle architecture with training, which may suggest that muscle hypertrophy was not an explanation for this increased stiffness. However, higher fascicle stiffness could be achieved with shifted myosin-heavy-chain (MHC) isoform composition of muscle fibers from slow (I) to fast (IIa), as shown by Liu et al. (2003) with combined strength plus ballistic stretch-shortening type-of training. Unfortunately, passive twitch was not measured or muscle biopsies taken in the present study in order to confirm the speculation. Malisoux et al. (2006) found some evidence that SSC training could also increase the cross-bridge mechanics of fast twitch muscle fibers by reporting increased normalized peak power of type IIa muscle fibers after 8 weeks of SSC training. Whatever the mechanism, it is suggested that an increase in fascicle stiffness after training enables the tendon to utilize more elastic energy since it is the difference in stiffness between these two structures that determines the amount of lengthening on them when force is applied (Zajac 1989). In addition, the shift of fascicles to a shorter position after training may have other functional relevance in the tendon by removing the tendon slack before the ground contact and therefore enabling a faster tendon stretch.

Average GaM outer tendon stiffness during the braking phase of hopping was on average 211 ± 95 N / mm, which is within the physiological range reported in *in vivo* studies that measured Achilles tendon stiffness during isometric contractions (Peltonen et al. 2012; Peltonen et al. 2013) and during one-legged hopping (Farris et al. 2012; Lichtwark and Wilson. 2005a). Tendon stiffness did not change with changes in hopping intensity. This supports the idea that tendon stiffness is not significantly influenced by viscosity and thus independent of the loading rate (Peltonen et al. 2013). When compared to young, the elderly generally have lower tendon stiffness (Karamanidis and Arampatzis. 2005; Kubo et al. 2003; Morse et al. 2005) so if training increases stiffness, this would counteract the effects of aging. However, contrary to our original hypotheses, stiffness did not change with training. There are several studies that have found an increase in outer tendon / tendon-aponeurosis stiffness after strength training (Onambele-Pearson and Pearson. 2012; Reeves et al. 2003) or alpine skiing training (Seynnes et al. 2011) in the elderly as well as after strength training (Kubo et al. 2006; Kubo et al. 2007) or isometric cyclic training in young (Arampatzis et al. 2007). It has been shown that tendon requires high strains in order to adapt (Arampatzis et al. 2007). Arampatzis et al. 2007 found increase in GaM tendon-aponeurosis stiffness after 14 weeks (4 days per week) of isometric cyclic training that caused high tendon strains (4.7%) but not with low strain (2.97%) training. Hopping training in the present

study was performed with 75% and 90% intensities from peak Fz and the average tendon strain during those intensities was 5.1 ± 2.3 % (relative to length during relaxed standing) which is considered very high in relation to the reported maximal physiological tendon strain values (Wren et al. (2001) reported failure strain value of 7.5 ± 1.1 % for human Achilles tendon substances) as well as with high strain rate of 43.0 ± 19.6 % / s. Therefore, the training intensity was probably as high as it could safely be. The training group performed on average 134 ± 28 jumps per training session and in total 4268 ± 638 jumps over the 11 week training period. There are several other studies that found unchanged tendon stiffness after plyometric training (Hansen et al. 2003; Houghton et al. 2013; Kubo et al. 2007) and Kubo et al. (2007) found that tendon stiffness increased after strength training but not after plyometric training. Lack of tendon adaptation after plyometric training as compared to that after strength training may suggest that in addition to high loading magnitude, a high loading duration per contraction is required for tendon adaptation, as suggested also by Arampatzis et al. (2010) and Kubo et al. (2001). In addition, it can be argued that since tendon stiffness is closely related to strength level (Stenroth et al. 2012), calf muscle strength may not have changed much with hopping training (Kyrolainen et al. 2005; Piirainen et al. 2014) and therefore also the stiffness remains unchanged. On the other hand, it must be noted here that the GaM outer tendon was measured in the present study, whereas most of the studies have measured the combined stiffness of the tendon-aponeurosis structure (e.g. Arampatzis et al. 2007; Kubo et al. 2006). Since it is known that the outer tendon and aponeurosis have different mechanical properties (Finni et al. 2003; Kubo et al. 2005; Magnusson et al. 2003), it may be that their adaptability also differs and therefore it can be speculated that adaptation might have occurred at the aponeurosis level, which was not investigated at the present study. Similar conclusions have been suggested before (Kubo et al. 2006). Another possibility is that a longer training period would be required for elderly tendon to increase its stiffness due to longer adaptation period to correct loading technique although changes have been observed in young individuals two months after the start of strength training (Kubo et al. 2012).

Although tendon stiffness remained unchanged with training, some training induced adaptations were observed in tendon function. First of all, tendon stretching and shortening amplitudes followed the changes in the MTU level and in tendon force and increased with training from 2-11W (figure 6). In addition those trained subjects that increased their jumping height the most from 2-11W also increased their tendon strain thus highlighting the importance of tendon function during this kind of short contact hopping. Finally, the tendon seemed to adapt beyond the level of MTU since tendon recoil relative to MTU shortening was higher in TG as compared to CG at 11W.

A few limitations of the present study must be highlighted. First of all, it must be noted that although the subjects of this study were randomly assigned for TG and CG, the groups were not perfectly similar at baseline. Although the difference in 100% jumping height was not statistically significant, there was a tendency for CG to jump better than TG at BEF. CG were also few years younger and had a trend for lower BMI as compared to TG (table 1). This difference between the subject groups at BEF is minor but is seen in many variables and somewhat complicates the results and interpretations although we believe that it does not affect the overall picture. Secondly, the superimposed twitch was not measured during MVCs and therefore it is not known whether the capacity to voluntarily activate calf muscles improved with training. If activation capacity was insufficient at BEF, this would cause us to overestimate the normalized EMG values of BEF condition and therefore possibly hide the improved neural drive due to training. However, the activation capacity of calf muscles during maximal plantarflexion has been shown to be high in the elderly (Barber et al. 2013) and therefore it is not expected to change greatly with training. Finally, had passive twitch been measured, it could have been used as an indicator of possible changes in MHC isoforms with training.

Why should the elderly perform hopping training?

When considering aging, it is known that force production capacity declines and movements become slower (Candow and Chilibeck, Lanza et al. 2003; Norris et al. 2007). Part of these changes are due to the aging process itself and part is due to a decrease in physical activity level, especially exercises that include rapid force production (Candow and Chilibeck. 2005; Morse et al. 2004). However, in order to be able to function independently and avoid falls, the elderly should also have a reserve for rapid force production in situations when balance needs to be corrected quickly after tripping. The present study showed that hopping training improved rapid force production in the elderly by decreasing the contact time and increasing the ground reaction force and RSI. Therefore, hopping training could possibly help elderly to retain and improve some rapid force production capacity. In addition, the short contact hopping performed in the present study that loads mainly the ankle joints could also help walking ability in elderly since the ankle joints are reported to be the weakest link during walking in elderly (Beijersbergen et al. 2013).

CONCLUSIONS

In conclusion, the present study suggests that an 11 week repetitive hopping training intervention can improve the jumping height and RSI in physically active elderly men. The improvement in performance was achieved with shorter GaM operating lengths after training and therefore increased fascicle stiffness and improved tendon utilization. Based on results of the present study, hopping training could be recommended for at least healthy fit elderly in order to retain and improve their rapid force production capacity.

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GRANTS

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

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FIGURE LEGENDS

Figure 1. Ankle and knee joint angles at contact instant, minimum angle and angle at take-off instant at BEF, 2W and 11W at 100% hopping intensity. # and ##; 11W significantly different from 2W (p<0.05 and p<0.01, respectively)

Figure 2. Changes (%) from BEF in A) jumping height, B) contact time, C) peak Fz and D) AJS at 100% hopping. * and **; significant training effect (p<0.05 and p<0.01, respectively), # and ##; significant group effect (p<0.05 and p<0.01, respectively)**.** AJS was calculated as the change in ankle joint moment (from contact to peak) generated by the right leg divided by change in ankle joint angle (from contact to min).

Figure 3. Reactive strength index (flight time divided by contact time) at different intensity levels at BEF, 2W and 11W. * and **; significantly different from BEF (p<0.05 and p<0.01, respectively). ##; significantly different from 2W (p<0.01).

Figure 4. GaM braking over push-off phase EMG ratios in hopping with different intensities at BEF, 2W and 11W. * and **: significant training effect (p<0.05 and p<0.01, respectively). ¤: significant difference between training and control groups (p<0.05).

Figure 5. The length-time curves of GaM MTU, outer tendon and fascicle as well the ATF-time curves during hopping with different intensities in TG and CG at BEF, 2W and 11W.

Figure 6. GaM A) MTU and B) outer tendon lengthening and shortening amplitudes during hopping with different intensities. Stretching amplitudes are calculated from length during contact instant to peak length and shortening amplitudes from peak length to length at take-off instant.* and **: significantly different from 2W (p<0.05 and p<0.01, respectively).
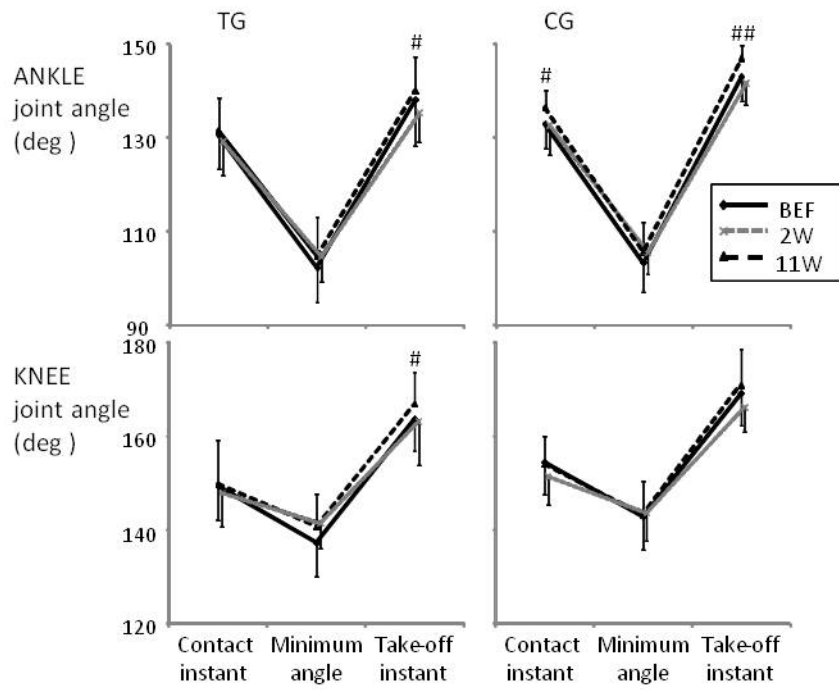
FIGURES AND TABLES

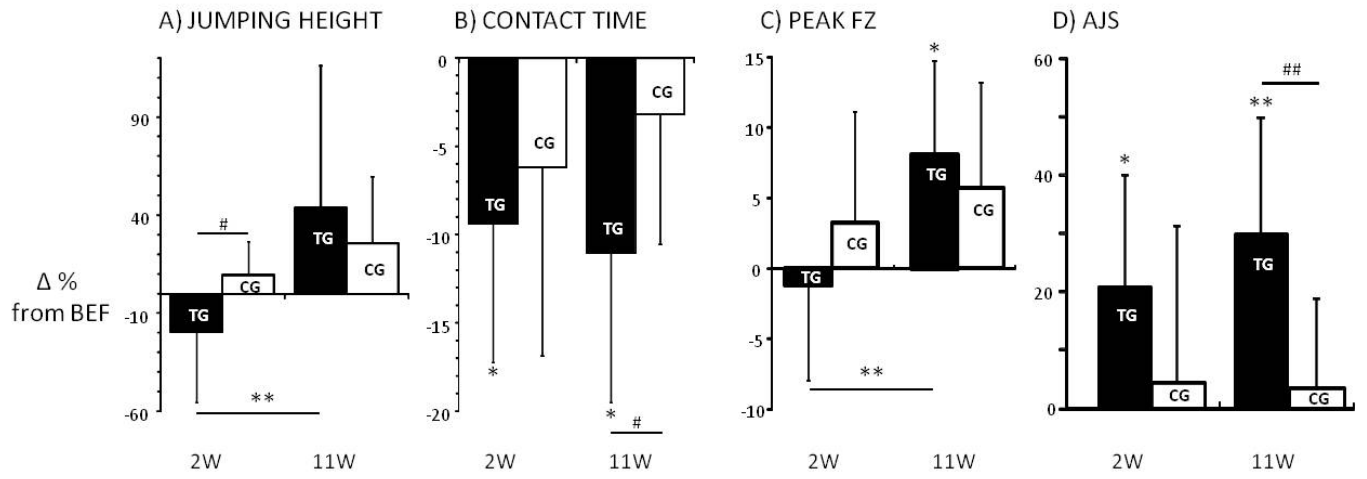Figure 1

Figure 2

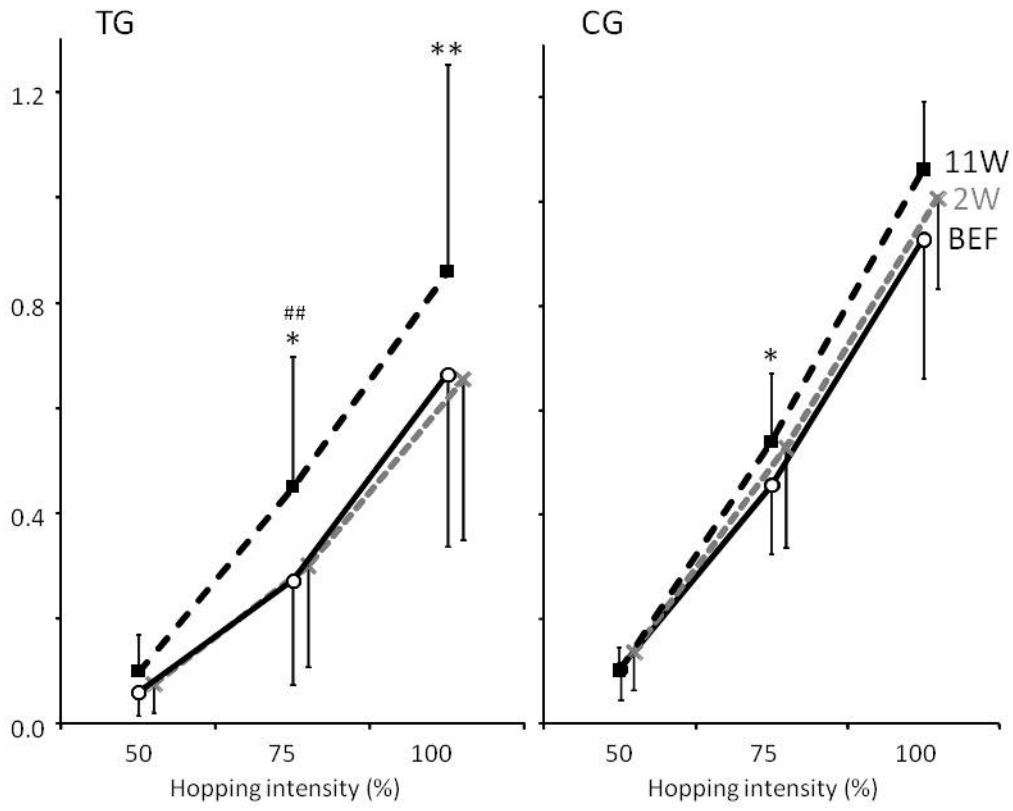A) JUMPING HEIGHT
B) CONTACT TIME
C) PEAK FZ
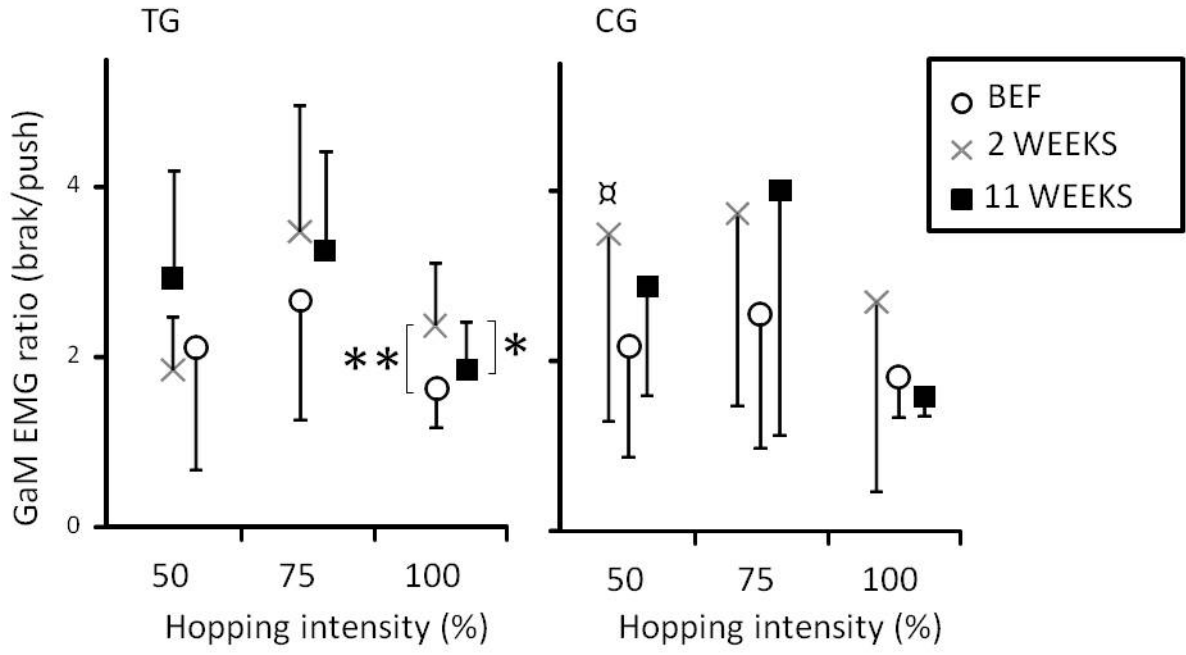D) AJS

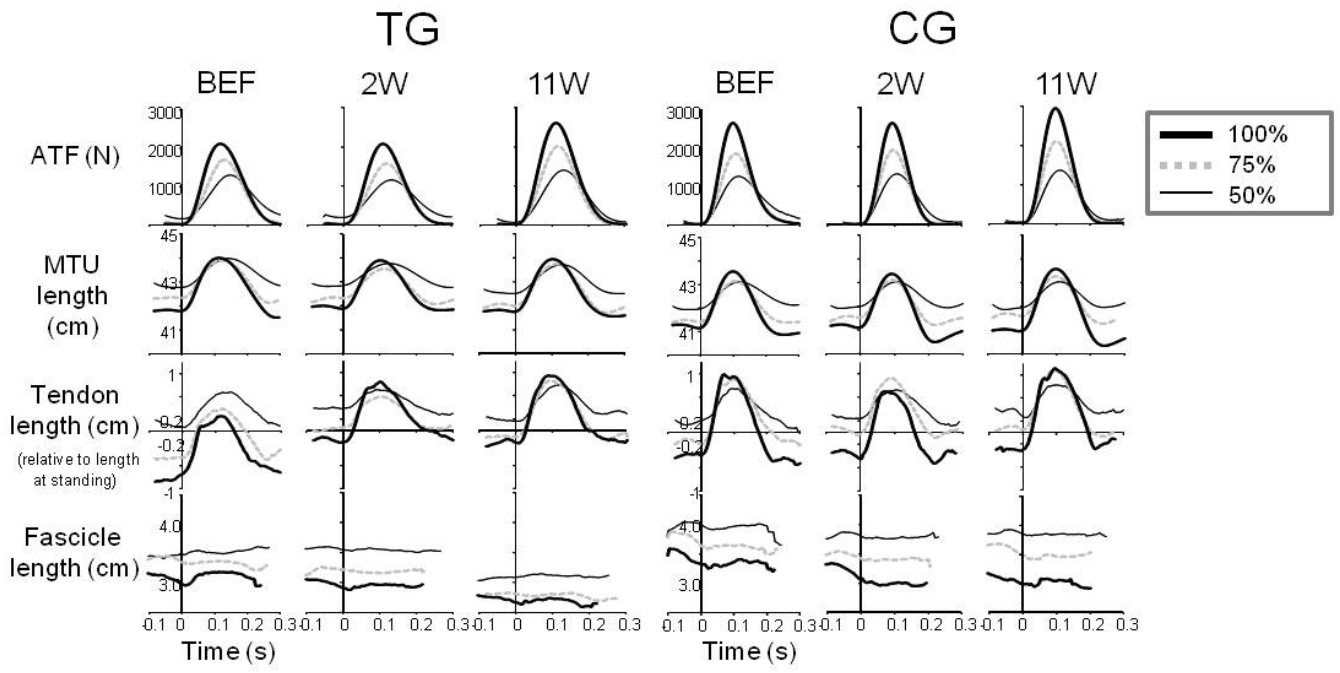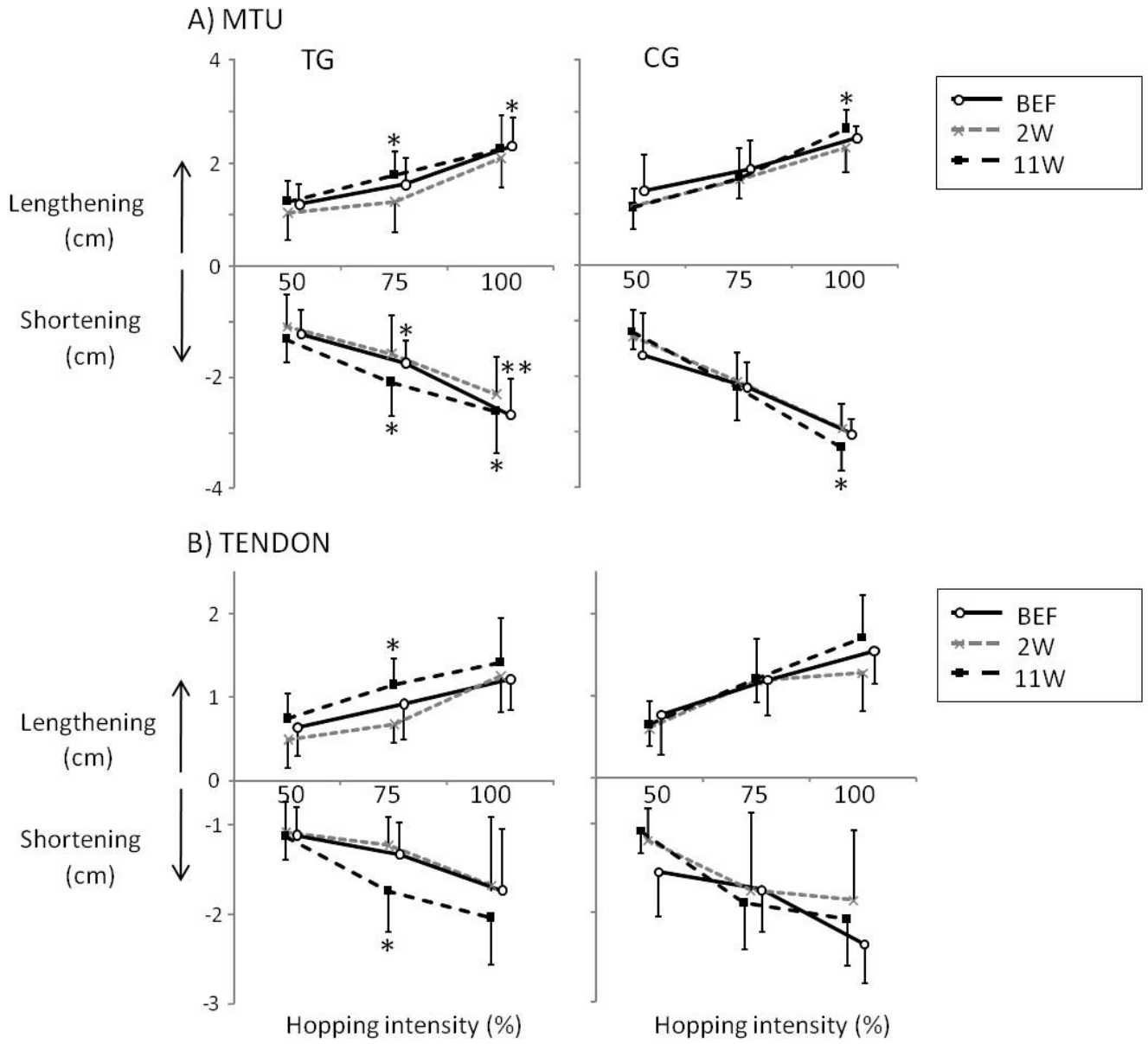Figure 3

Figure 4

Figure 5

Figure 6

Table 1. Background information of the subject groups. [#] Supervised training means training with the supervisor outside the present study e.g. in local senior gym. *) Exercise types are listed in the order the subject groups reported they performed them.

	TG (n=10)	CG (n=10)	P value
Age (y)	73.1 ± 4.4	70.9 ± 4.4	0.28
Height (cm)	170.5 ± 7.4	171.9 ± 3.9	0.61
Weight (kg)	76.8 ± 9.2	73.4 ± 8.7	0.40
BMI (kg/m^2)	26.4 ± 2.5	24.8 ± 2.4	0.16
Exercise times / week	4.5 ± 1.8	3.6 ± 1.2	0.21
Exercise hours / week	7.4 ± 5.4	4.8 ± 2.2	0.24
Participation in supervised training [#]	6/10	9/10	0.13
Preferred exercise types *)	Walking, skiing, gymnastic exercises	Gymnastic exercises, walking, cycling	

Table 2. Progression of the exercise intervention (adopted from Rantalainen et al. 2011).

Week	1	2	3	4	5	6	7	8	9	10	11
Sets * Intensity	4*75	2*75	1*75	1*75	1*75	2*75	2*75	2*75	2*75	2*75	2*75
(% of maximal GRF)		3*90	4*90	4*90	4*90	5*90	5*90	5*90	5*90	5*90	5*90

Table 3. Correlation coefficients between the selected parameters and maximal jumping height (cm) at 11 WEEK measurements in trained and in controls. n= 10 trained, n= 10 controls. * and **: p<0.05 and p<0.01, respectively.

	Peak ATF	GaM fascicle shortening in push-off phase	GaM MTU stretch	GaM MTU shortening	GaM tendon strain	GaM tendon shortening
TG	0.86 **	-0.66 *	0.74 *	0.76 *	0.64 *	0.66 *
CG	-0.35	-0.22	-0.50	-0.31	-0.33	-0.10