MUSCLE CO-ACTIVATION AND GROUND REACTION FORCES DURING STAIR WALKING IN OLD AND YOUNG WOMEN

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ABSTRACT

Force production and co-activation of different leg muscles are essential elements of the moving strategy in performing daily living tasks such as stair walking. The purpose of this study was to investigate the magnitude and timing in muscular antagonist co-activation of leg muscles in relation to vertical ground reaction force (GRF) in old (age=65-82, n=19) and young (age=23-29, n=10) women. The study is part of a larger intervention study that is being carried out in Odense, Denmark. The differences in muscular antagonist co-activation and in the shape of GRF curve during ascent at maximum velocity (AMV) and at self selected velocity (ASV) and during descent at self selected velocity (DSV) on a nine-step staircase were studied. A force plate was mounted on the fifth step. EMG activity was measured from the agonist muscles vastus lateralis (VL) and medialis (VM), rectus femoris (RF), soleus (Sol), gastrocnemius lateralis (GasLat) and from antagonist muscles biceps femoris (BFcl), semitendinosus (ST) and tibialis anterior (TA). The statistical analyses applied were an unpaired two-tailed *t*-test, analysis of covariance, Pearson correlation analysis (r), and linear regression.

The maximum values (N/kg) of GRF for the old subjecs were 135 ±23 (AMV), 112 ±11 (ASV), 148 ±24 (DSV) and for the young subjects 192 ±16, 117 ±13, 160 ±14, respectively. During AMV, both groups showed a single-peak GRF waveform. In contrast, a double peak GRF waveform was observed during ASV in both young and old subjects. Large variations in GRF were observed during DSV, with one, two or many smaller peak waveforms for both groups. However, there were differences between the old and young subjects in the different phases of the vertical GRF curve during stair ascent and descent. Compared to young subjects, old individuals demonstrated elevated antagonist muscle co-activation in the thigh during AMV in entire stance phase ($p=0.010$) and loading slope ($p=0.024$), during ASV in entire stance phase ($p=0.013$) and mid stance phase ($p=0.011$), and during DSV in entire stance phase ($p=0.034$), the first force peak ($p=0.039$), loading phase ($p=0.002$) and in the loading slope ($p=0.001$). For the calf co-activation, there were no significant differences between old and young subjects during AMV. During ASV old subjects had elevated co-activaton in the first peak ($p=0.026$) and young subjects in the unloading phase ($p<0.001$), and in the second peak during DSV. Time parameters of step cycle showed old subjects to be slower, their step cycle duration and complete stance phase to be longer than in young subjects. The long complete stance phase and step cycle duration were associated with low GRF parameters for the old subjects when ascending (r=-.561 - -.924, p<0.001-0.05) and for the young subjects when descending the stairs (r= -.645 - -.759, p<0.01-0.05).

The differences in antagonist muscle co-activation may be caused by older subjects compensating for a loss in maximal muscle strength, therefore adopting a joint walking strategy that involves elevated joint stiffness, achieved by means of elevated agonist-antagonist muscle co-activation. Further, the present data indicate that old subjects operate nearer to their maximum physiological capacity while ascending and descending stairs, and perhaps therefore muscle co-activation is elevated to perform the task safely. To elucidate these notions more closely, further studies with larger groups of ageing men and women are needed, preferentially including measurements with multiple force plates and more varied stepping velocities.

Keywords: aging, co-activation, EMG, gait, muscle, stair walking, vertical ground reaction force

ABBREVIATIONS AND DEFINITIONS

GRF = Ground reaction force
MVC = Maximal voluntary contraction
Fz = Vertical force value
Fz2 = The first peak of the vertical GRF curve
Fz3 = The mid-phase minimum point of the vertical GRF curve
Fz4 = The second peak of the vertical GRF curve
bn = The loading slope of the vertical GRF curve from heel touch-down to 80% of the first peak
en = The unloading slope of the vertical GRF curve from 80% of the second peak to toes take-off
N = Newton
AMV = Stairs ascent at maximum velocity
ASV = Stairs ascent at self selected velocity
DSV = Stairs descent at self selected velocity
VL = Vastus lateralis
VM = Vastus medialis
RF = Rectus femoris
BFcl = Biceps femoris caput longum
ST = Semitendinosus
Sol = Soleus
GasLat = Gastrocnemius lateralis
TA = Tibialis anterior

GRF parameters:
#1 = Mean values of entire stance phase (% BW)
#9 = Value at the first Fz peak, known as Fz2, GRF (% BW)
#10 = Values at Fz mid-phase minimum point, known as Fz3, GRF (% BW)
#11 = Values at the second Fz peak, known as Fz4, GRF (% BW)
#12 = Mean values in the mid-phase of stance phase, from the first peak to the second peak, GRF (% BW)
#13 = Mean values in the first part of the stance phase, from heel touch-down to the first peak (loading phase), GRF (% BW)
#14 = Mean values in the final part of the stance phase, from the second peak to foot take-off (unloading phase), GRF (% BW)
#15 = Fz loading slope, known as bn, from heel touch-down to 80% of the first peak, ΔGRF/Δtime (NS^{-1} % BW^{-1})
#16 = Fz unloading slope, known as en, from 80% of the second peak to foot take-off, ΔGRF/Δtime (NS^{-1} % BW^{-1})

Time parameters of step cycle:
#5 = Step cycle duration
#6 = Step frequency
#7 = The fractional part of stance phase duration relation to step cycle duration
#11 = Time for heel touch-down Fz signal
#12 = Time for toes take-off Fz signal
#12-#11 = Complete stance phase

APPENDICES

1 INTRODUCTION

Several studies have been made from staircase walking. The first documented investigations of stepping tasks began as early as 1887 with Muybridge`s scinematographic depiction of adult subjects ascending and descending stairs (Muybridge 1955). A number of stair walking studies have focused on subjects with different kinds of leg injuries (Andriacchi 1990, Berchuck et al. 1990, Kowalk et al. 1997, Thambyah et al. 2004) or in patients with diseases affecting leg function (Duran et al. 1993, Kaufman et al. 2001, Wu et al. 2005). Muscle activation research during stair walking with healthy subjects was first studied by Joseph & Watson (1967). After that, Townsend et al. (1978) and Andriacchi et al. (1980) have added to the knowledge about the muscle mechanism and muscle activation during ascent and descent of stairs. James & Parker (1989) were the first in studying muscle activity during stair ascent and descent in the elderly.

Cavanagh et al. (1997) reported that stair negotiation is a complex locomotor task in which the musculoskeletal system relies heavily on somatosensory and visual input. As Riener et al. (1999) and Nadeau et al. (2003) have commented, stairs are frequently encountered obstacles in daily living, and in particular for older people they can be very challenging (Nadeau et al. 2003). Differences in the kinetic and kinematic gait pattern between old and young people during walking and stepping have been studied by DeVita & Hortobágyi (2000). The step length was 4% shorter and cadence was 4% higher in elderly adults compared to young adults. Older persons have decreased step height, which might come from central nervous system diseases, multiple sensory deficits, or from fear of falling (Tinetti & Speechley 1989).

Muscle activation patterns change with age. Older people appear to use higher co-activity in lower extremity agonist-antagonist muscles while performing daily living tasks (Häkkinen et al. 1998a, Hortobágyi & De Vita 2000, Macaluso et al. 2002). The antagonist muscle co-activition is likely to increase joint stiffness which enhance the stability in the lower extremities (Barratta et al. 1988). Further, elderly people may adopt a motor strategy with elevated antagonist co-activition in order to reduce movement variability. This may be an effort to compensate for increased joint laxity and reduced muscle strength (Hortobágyi & DeVita 2006). Simoneau et al. (1991) have suggested that healthy elderly women respond to sensory challenges by adopting safer strategies during stair descent.

Vertical GRF has been widely studied in level walking situations for example, by Simonsen et al. (1997), White et al. (1999) and McCrory et al. (2001). However, few studies have performed gait analysis during stair ascent and descent (Christina & Cavanagh 2002, Stacoff et al. 2005, Hortobágyi et al. 2005). GRF describes the reaction force provided by the supporting horizontal surface (Enoka 1994, 46-47). An M-shaped force-time curve with biphasic force peaks is observed during stair ascent and descent (Christina & Gavanagh 2002, Riener et al 2002, Stacoff et al. 2005).

Although many studies have examined stair ascent and descent, few have obtained GRF and agonist-antagonist muscle EMG measurements during stair walking, and even fewer have analyzed real staircase walking with multiple steps. However, there are two studies where the EMG and GRF have been analysed together, but the studies were from level walking (Simonsen et al. 1997) and stair walking in children (Lobo da Costa et al. 1995). No one has yet studied the degree of muscular antagonist co-activation relation to the vertical GRF in old subjects, and that was the main interest of the present study. The other purposes of this study were to investigate muscular antagonist co-activation and vertical GRF profile in older women as compared to younger women during stair descent and ascent. This study is part of an intervention study that is being carried out in Odense, Denmark (Larsen et al. in press).

2 REVIEW OF LITERATURE

The staircase research has been performed using different kinds of stair designs. According to Riener et al. (1999), a commonly used design is to use stairs with selected number of steps with a force plate on the last step, as in studies of Andriacchi et al. (1980) and McFadyen & Winter (1987). This kind of staircase design allows a collection of kinetic data for only one step in each trial (Riener et al. 1999). Another design places two separate force plates on two steps of stairs, and the measurements are performed separately either for the left and right side of the staircase as in Zachazewski`s et al. (1993), or for consecutive steps as in Besser`s et al. (1993) and Yu`s et al. (1996) studies. In those staircases, errors in measured ground reaction forces were relatively small (Riener et al. 1999).

Müller et al. (1998) studied the influence of stair inclination on muscle activity in healthy young men. It was concluded that with increased step height, higher foot clearance required an increase and a change in timing of muscle activity of several leg muscles. Different kinds of stairways, risers, and treads have been investigatedby Irvine et al. (1990). Their subjects were asked to identify stairways that they considered acceptable. The results concluded that the optimum riser is 183 mm and the optimum treads are 279 or 300 mm. These dimensions are acceptable for young and old subjects in both genders.

Force plates and their usage in stair walking situations have been examined by Besser et al. (1993). They suggested that with appropriate modifications, GRF can be measured using force plates for ascending and descending (Besser et al. 1993). Reproducibility of the kinematic analyse measurements of stair ascent and descent in healthy adults has been investigated and found to be acceptable despite the possible causes of intra subject variances and the variation in motor performance (Yu et al. 1997).

2.1 The mechanics of stair walking and differences to level walking

Joseph & Watson (1967) were the first to investigate muscle activation during stair ascent and descent. They had six healthy adult men who walked at their own, natural velocity. The study was performed to see if there was a consistent pattern of muscle activity among individuals, and what the sequence and extent of activity of the muscles involved would be. Also Anriacchi et al. (1980) studied lower-limb mechanics during stair ascent and descent at individual velocity in ten adult men. They stated that stair ascent and descent from a mechanical point of view are quite different from level walking (Anriacchi`s et al. 1980). The study of stair ascent at individual velocity in healthy adults over 40 years showed significantly longer mean cycle duration and a shorter proportion of time in stance to stair ascent compared to level walking (Nadeau et al. 2003). In stair walking, gait cycle duration, swing and stance phase duration, and cadence and velocity appeared to be related to subject height. The cyclic pattern of the lower limbs during stair ascent and descent is very similar to the cyclic pattern of level walking. (Livingston et al. 1991.)

During ascent and descent the body is carried in a net vertical direction with forward translation. That results in basic muscle action and range of motion at the joints which are different from those in level walking. (Andriacchi et al. 1980, McFadyen & Winter 1988.) Differences between level walking and stair ascent and descent have been explained in the necessity to raise or lower the body while effecting progressing to another stair level (James & Parker 1989). Another explanation is that the differences are in the range of motion of the different joints during gait, in the basic muscle activities and in the maximum joint forces and moments (Andriacchi et al. 1980).

McFadyen & Winter (1988) and Nadeau et al. (2003) have noticed that stair ascent is characterised by large moments and powers produced in the sagittal plane. The forces and powers are higher in stair ascent than in level walking (Costigan et al. 2002), and the largest moments are in descending (Andriacchi et al. 1980). A considerable amount of these moments and powers are required to support and propel the body against gravity and to generate movements that advance the body forward in the plane of progression (Eng & Winter 1995). Greater demands of stair walking are also made on balance mechanisms, particularly during the period of single limb support. Stair descent is accomplished largely by the influence of gravity, and eccentric muscular action is predominant during body support in providing a restraining function. (James & Parker 1989.) Duncan et al. (1997) have investigated that stair descent had greater variance ratios of joint powers than in stair ascent, given the variability in foot placement when descending a set of stairs.

The muscle activation and movement patterns of the right leg in load-carrying during stair ascent in 15 healthy men have been studied by Moffet et al. (1993). They suggested that the speed of forward progression must be considered in the interpretation of EMG levels during stair ascent. Yang & Winter (1985) have reported that an increase in speed has closely linked to higher EMG levels during walking, and those changes were muscle specific. Tata et al. (1983) have reported that EMG amplitude levels of the quadriceps femoris muscle in the stair cycle were higher in ascending than descending the stairs, and during descent the cadence value was greater than during ascent of stairs.

2.1.1 Stair ascent

During stair ascent, the lower limb functions to support and balance body weight and also raise the weight onto the supporting step (Wu et al. 2005). Stair ascent mainly involves pulling and pushing the body through concentric contraction of the rectus femoris, vastus lateralis, soleus and medial gastrocnemius. Ascent consists primary of a transfer of muscle energy into potential energy for the body. (McFadyen & Winter 1988.) Stair ascent commands greater stability than level walking and requires longer double support and shorter single limb support phases (Zachazewski & Riley 1993).

In normal stair ascent, the stance phase varies from 50% to 65% and swing phase varied from 35% to 50% of the ascent cycle (Livingston et al. 1991, Zachazewski & Riley 1993). Zachazewski & Riley (1993) described temporal phases from each stride normalized from 0% (first contact) to 100% (subsequent contact of the same foot). The whole stance phase is approximately 65% of the stair ascent cycle. Foot contact (0-2% of the stair ascent cycle), weight acceptance (0-17%), vertical thrust (2-37%), single limb support (17-48%), forward continuance (37-51%) and double support (48-65%). Swing phase consisted the remaining 35% of the stair ascent cycle.

In stair ascent, the tibialis anterior muscle is active from the beginning of swing phase until mid-swing phase, and soleus from the beginning of the supporting phase until the opposite limb is firmly placed on the next step (Joseph & Watson 1967, Townsend et al. 1978, Andriacchi et al. 1980). The rectus femoris is active during the supporting phase (Joseph & Watson 1967, Townsend et al. 1978), similarly to vastus medialis (Townsend et al. 1978, Andriacchi et al. 1980). The hamstring muscle group is active during the swing phase and supporting phase (Joseph & Watson 1967), and also during the latter part of swing and throughout most of the stance phase (Townsend et al. 1978). The gastrocnemius is active from mid-stance to end of stance phase. At the end of the stance phase, biceps femoris becomes active and remains active through mid-swing phase. (Andriacchi et al. 1980.) The gluteus medius is contracted during the supporting phase and in some subjects also during swing phase. Gluteus maximus is active in the supporting phase. (Joseph & Watson 1967.)

2.1.2 Stair descent

Stair descent is acquired through control of the force due to gravity by eccentric contractions of the same muscles as in ascending. In the descent, the potential energy has to be dissipated by the muscles. (McFadyen & Winter 1988.) During descent this process is reached first by a transfer of potential energy into kinematic energy (Riener et al. 2002).

In stair descent, the variation of stance and swing phases appears to be greater than in stair ascent, which varies from 19% to 68% in stance phase and from 32% to 64% in swing phase (Livingston et al. 1991, Zachazewski & Riley 1993). Zachazewski & Riley (1993) found that the stance phase comprises approximately 68% of the total stair descent cycle. They subdivided stance phase of stair descent into weight acceptance (0-14% of stair descent cycle), forward continuance (14-34%), and controlled lowering (34-68%). Single limb support accounts for 39% of the stance phase (14-53% of each cycle), double support occurs at the beginning (0-14% of stair descent cycle) and end (53-68% of stair descent cycle) of stance phase. Swing phase consists the remaining 32% of stair descent and is divided into leg pull through (68-84% of stair descent cycle) and foot placement (84-100% of stair descent cycle). Like in stair ascent, weight acceptance involves stance limb loading until single limb support is attained.

In stair descent the tibialis anterior shows a biphasic activation pattern. It is active in mid-swing phase and again at the beginning of the supporting phase (Joseph & Watson 1967, Townsend et al. 1978, Andriacchi et al. 1980). Soleus is active throughout most of the supporting phase (Joseph & Watson 1967), same as the gastocnemius (Townsend et al. 1978) which becomes active just before foot strike (Andriacchi et al. 1980). The rectus femoris is active coincident with the tibialis anterior, although becoming active earlier in both phases (Joseph & Watson 1967, Townsend et al. 1978). The hamstring group is active during the swinging phase (Joseph & Watson 1967), but in Townsend et al. (1978) study, the hamstring group was active also around foot touch down. The biceps femoris is active at the start of swing phase and it remains active through mid-swing (Andriacchi et al. 1980).The gluteus medius shows activity during the late part of the swinging phase and most of the supporting phase. The gluteus maximus has only a small amount of contraction at the beginning of the supporting phase. (Joseph & Watson 1967.) The greatest variability with the dominant pattern was observed for the hamstrings in both stair ascent and descent. The most consistent muscle was rectus femoris. (Townsend et al. 1978.)

2.1.3 Stair walking in older people

The earlier studies by Joseph & Watson (1967), Townsend et al. (1978) and Andriacchi et al. (1980) of muscular activity patterns during stair walking have been performed with young men. James & Parker (1989) were the first in studying lower limb muscle electromyographic activity during stair ascent and descent in older men and women, aged 76-83. They suggested that old age is associated with deterioration in motor performance. They used staircase with 10 steps and EMG measurements from lower limb muscles. They noticed that their subjects walked with more of a flexed position of the trunk than young people, which may result in different muscle activity in the biceps femoris in old subjects as compared to young subjects.

During stair ascent, older people use rectus femoris before initial foot contact (activity began 20-40 ms before) and peaks during weight acceptance at approximately 10% of the support phase. Some subjects also have a second burst of activity at a moderate level during mid-swing lasting approximately 30% of the limb swing phase. For the vastus medialis, subjects had one period of maximum activity for about 10-15% of the body support phase. The most variable muscle is the biceps femoris, particularly during single limb support. The activity starts from 50-70% of the swing phase, and it increases during the remainder of this phase to a moderate level by foot contact, reaching a peak early in single support phase. In half of the subjects activity ceased, and in the other half activity finished at approximately 60% of single leg support, having a second burst of activity at beginning of swing phase. The gastrocnemius is active from 40% of the body support period and has a peak between 70-80% of the body support duration. Some subjects have a second activity phase at a moderate level in 80-90% of the limb swing phase, which continues until early body support phase. (James & Parker 1989.)

In stair descent, rectus femoris is active longer than in stair ascent. It becomes active during 50-70% of the limb swing period and peaks when the limb reaches body support phase.

Activity increases again to a second peak after mid support phase and ceases close to weight transference, continuing to 20% of the limb swing phase. The activity of the vastus medialis begins 60-70% of the swing phase and continues throughout the period of body support, and ends during weight acceptance. The first peak occurrs at foot contact and the second, higher peak 75-90% of the body support phase. (James & Parker 1989.)

For older subjects, the biceps femoris appears to be the most variable muscle during descent. The activity begins during swing from 30% to as late as 70% of this phase, continuing into the body support phase. The peak EMG activity occurs during early weight acceptance, continuing for half of the subjects during early and mid single support, and for others during weight transference. For those with early activity, the second peak is at the beginning of weight transference, and the third burst of activity is during 40-50% of the swing phase. The maximum EMG activity occurs in most of the subjects at weight acceptance; however, in others it is either at the beginning of weight transference or early limb swing. (James & Parker 1989.)

For the tibialis anterior the activity is biphasic. After foot contact, activity increase to a moderate level during early single limb support, and has a peak at 12-25% of the body support phase. The second, very high peak occurs at 5-10% of the swing phase. The activity of gastrocnemius begins at mid-swing, and increases steadily to reach a peak soon after foot contact. Half of the subjects have the second activity continuing from 40% and ceasing at 70% of the support phase. The peak EMG occurs during weight acceptance at 10% of the body support phase. (James & Parker 1989.)

Hortobágyi & DeVita (2000) reported old people to have greater muscle preactivity compared to young people in the vastus lateralis, biceps femoris, gastrocnemius and tibialis anterior during downward stepping from a platform set at 20% body height. Further, they found significant positive relationships between muscle pre- and co-activation during downward stepping and leg stiffness.

2.2 GRF in stair walking

GRF has been studied both during walking (Elfman 1939, Drillis 1958, Chao et al. 1983, Winter 1984, Herzog et al. 1989, Kirkpatrick et al. 1994, Beard et al. 1996, Giakas &

Balztapoulos 1997, Simonsen et al. 1997, White et al.1999, McCrory et al. 2001) and in running situations (Alexander 1984, DeVita & Bates 1988). Simonsen et al. (1997) have also coupled vertical GRF and EMG measurements from lower limb muscles during level walking. Notably, vertical GRF in level walking has been noticed to be highly repeatable within individuals (Kirkpatrick et al. 1994, Yu et al. 1997, White et al. 1999).

Vertical GRF during stair ascent and descent has not been studied extensively. With stairs, there has to be a minimum of five steps to include the “transition” phase (Stacoff et al. 2005), which covers the first two steps, and shift into a steady state phase of walking stairs (Yu et al. 1997, Christina & Gavanagh 2002). There are only a couple of studies that used a minimum of five steps (McFadyen & Winter 1988, Lobo da Costa & Amadio1995, Christina & Gavanagh 2002, Riener et al. 2002, Stacoff et al. 2005). GRF on stairs have studied by Lobo da Costa & Amadio (1995), Savvidis & von der Decken (1999), Christina & Gavanagh (2002), Riener et al. (2002) and Stacoff et al. (2005). The above studies have reported changes in the “M” shape curve (Perry 1992, 415-417) known from level walking. The “M” shape curve (i.e. with biphasic force peaks) was changed in the way that the second peak was enlarged during stair ascent while the first peak was enlarged during stair descent (Lobo da Costa & Amadio 1995; Savvidis & von der Decken 1999; Christina & Gavanagh 2002; Riener et al. 2002; Stacoff et al. 2005). Stacoff et al. (2005) also found that during stair descent the curves showed large variations with or without a second maximum. For stair ascent, the maximum values of GRF were reported to be between 1.2 and 1.7 Body weight (BW) (Lobo da Costa & Amadio 1995, Savvidis & von der Decken 1999) and for stair descent between 1.4 and 2.6 BW (Lobo da Costa & Amadio 1995, Savvidis & von der Decken (1999), Christina & Gavanagh 2002).

The changes in the vertical GRF from level walking to stair ascent is small, but the change becomes larger from level gait to stair descent. In stair descent the first peak and loading slope of GRF showed great increase compared to level walking and stair ascent. GRF in foot takeoff phase, the second peak and unloading slope were increased during stair ascent and decreased during stair descent. (Stacoff et al. 2005.) In stair ascent at foot contact, there isa fast increase in a vertical GRF reaching the first of two maximums at the start of single limb support (17% of the stair ascent cycle). After the first peak, vertical GRF decreases until mid stance (34% of the stair ascent cycle), and thereafter it increases again to reaching its second maximum as double support is starting (51% of stair ascent cycle). (Zachazewski & Riley

1993.) During ascent, the main phase of energy production takes place at the foot takeoff phase, where the GRF is higher compared to descent (Riener et al. 2002). Younger people showed a higher first peak, loading and unloading slopes compared to old subjects during ascent (Stacoff et al. 2005).

In stair descent, there is a fast increase in vertical GRF reaching the first of the two maximums at the start of single limb support (14% of stair descent cycle), then vertical GRF decreases as in stair ascent until mid stance (32% of stair descent cycle). Thereafter, vertical GRF increases reaching the second of two maximums at the same time as the initiation of the second double support phase (53% of stair descent cycle). (Zachazewski & Riley 1993.) During stair descent, Riener et al. (2002) found higher forces produced at the beginning of the stance phase than during ascent. During descent, age affects the second peak, where older people have weaker foot takeoff as compared to younger people (Christina & Cavanagh 2002). There was a trial-to-trial variability of approximately 5-10% from the first peak to the second peak in stair ascent and descent. Stair descent showed higher variability as compared to stair ascent. The loading and unloading slopes showed a variability of 10-15% for stair ascent and 15-20% for stair descent. (Stacoff et al. 2005.)

The stair step location had a significant effect on the vertical GRF first peak and on the second peak when people were descending. The first peak was significantly greater at stair number 4 as compared to stair number 2, vise versa to the second peak. The investigators noticed that older people used a more cautious strategy in descending the stairs than younger people. The difference may result from a lack of control at heel touchdown or increased joint stiffness. (Christina & Cavanagh 2002.)

2.3 Antagonist muscle co-activation

Enoka (1994, 254) has defined co-activation as concurrent activity of agonist and antagonist muscles which surround a joint. The primary role of co-activity is to increase joint stiffness which affects the stability of upper and lower extremities (Barratta et al. 1988; DeLuca & Mambrito 1987). The human body muscles generate forces in opposing directions which why it is possible to control separately both the torque and the stiffness at the joint. The difference between the torque of the agonist and antagonist muscle set is called the net torque at a joint, and the joint stiffness is the sum of the individual stiffness of the agonist and antagonist muscles. Although the value of these two variables can be results from either high net torque and low joint stiffness or low net torque and high joint stiffness. (DeLuca & Mambrito 1987.) A neural control circuit consists of two kinds of commands, namely a centrally mediated reciprocally organized flexion and extension command, and a common co-activation command to both agonist and antagonist muscles. These can be used to explain motor unit activation in agonist-antagonist muscles during natural movement in human (DeLuca & Mambrito 1987). This control circuit permits both co-activation and reciprocal activation of given sets of agonist-antagonist muscles (DeLuca & Mambrito 1987). Further, the cerebellum plays an important role in co-activation (Smith 1981).

Hansen et al. (2002) have studied two different input systems which are involved in the co-activation of the antagonist muscles. The first system is in-phase coupling of the muscles, in which agonist and antagonist muscles are co-activated without any opposing inhibition. This system is used in tasks where co-activation is essential in order to increase the stiffness of the joints. The second system is out-of-phase coupling (central trough) which controls extension/flexion movements. It assists the antagonist muscle in relaxation during agonist contraction. (Hansen et al. 2002.)

Häkkinen et al. (1998a) noticed that voluntary activation of the agonist and antagonist muscles seems to vary depending on the type of muscle action and time duration of the action. In dynamic movement there is a concentric agonist muscle contraction simultaneously with varying degrees of eccentric antagonist contraction (Aagaard et al. 1995). Rapid movements over a small range of motion are accosiated with large antagonist co-activation, and slow movements over a large range of motion are linked to small co-activity (Mardsen et al. 1983). In the fastest movements the agonist is primarily responsible for the distance moved and the antagonist muscle provides an effective means of reducing movement time in fast arm movements (Wierzbicka et al. 1986).

During isokinetic knee extension, antagonist co-activation of hamstrings has suggested to counteract to the movement and provide stability to the knee joint (Solomonow et al. 1987; Barratta et al. 1988; Draganich & Vahey 1990). Aagaard et al. (2000) examined the antagonist moment exerted by the hamstrings during slow isokinetic knee extension. There were significant amounts of antagonist hamstring EMG throughout the range of joint motion. The amount of antagonist co-activation was always greater in the lateral hamstring muscles (biceps femoris caput longum; 30%) compared to the medial hamstrings (semitendinosus, 10%) during maximal agonist quadriceps contraction. They also found that antagonist hamstring co-activation was greater towards full knee extension (10-30°) than in midrange of joint movement (40-60°) (Aagaard et al. 2000).

McFadyen & Winter (1988) discovered co-activation in early stance phase of stair descent in tibialis anterior and soleus in their study of stair ascent and descent in healthy adults. They noticed that all muscles (vastus lateralis, semitendinosus, gluteus maximus, medial gastrocnemius, soleus, tibialis anterior) except rectus femoris and gluteus medius had greater mean activity for ascent as compared to descent. This was attributed to a more optimal position of the body while descending the stairs. (McFadyen & Winter 1988.)

2.4 Muscle co-activation in old people

Older people have greater amounts of activity in antagonistic muscles than younger people (Woollacott et al. 1988; Manchester et al. 1989; Goggin & Meeuwsen 1992; Häkkinen et al. 1998a; Tracy & Enoka 2002). Men aged 65 years old showed greater muscle activation of the antagonists during the isometric and dynamic knee extension actions than men at 40 years old (Izquierdo et al. 1999). Old healthy subjects may demonstrate higher co-activity than young subjects regardless of the type of ratio during level walking, stair ascent and stair descent. When evaluating the EMG results, older subjects demonstrated a 1.6-fold greater activity in biceps femoris to vastus lateralis ratio, and a max ratio of 2.8-fold greater co-activity as compared to younger subjects. Using the vastus lateralis/vastus lateralis max ratio, older subjects had 1.5-fold greater co-activity than young subjects. Likewise, gastrocnemius/tibialis anterior ratio was higher in older subjects. (Hortobágyi et al. 2005.)

The above differences in antagonist muscle co-activation strongly indicate that elderly individuals typically rely on greater amounts of joint stiffness than young adults (Woollacott 1993). Muscle activities tended to be prolonged in older people for the soleus, gastrocnemius and biceps femoris muscles of the stance leg when subjects were stepping to regain balance during a forward fall. This finding has been asserted to be a consequence of older people employing motor strategies involving elevated antagonist muscle co-activation in order to stiffen the joints (Thelen et al. 2000). Older people use co-activation of the agonist-antagonist muscles to stabilize the ankle joint (Melzer et al. 2001) and knee joint (Hortobágyi & DeVita

2000). This reduced the amount of movement they had for controlling and maintaining posture (Melzer et al. 2001) and therefore increased lower extremity stiffness (Hortobágyi & DeVita 2000).

Hortobágyi & DeVita (1999), (2000) have studied lower extremity stiffness during stepping down from a platform adjusted to 10% and 20% of body height to a force plate, in young and old subjects. Older subjects had 50% greater lower extremity stiffness and 28% less linear shortening of the limb as compared to younger subjects. Old people performed downward stepping with a more erect lower limb position, resulting in a stiffer leg and safer movement strategy. Because old people have a multitude of motor system impairments, it is possible that they would employ a compensatory strategy to safely negotiate a dynamic external enviroment. The older subjects experienced reduced adaptability of their aged neuromuscular systems to greater motor challenges. The increased co-activity in older people must be the result of a centrally-mediated and generalized voluntary muscle activation. (Hortobágyi & DeVita 1999, 2000.)

Old people perform near their maximal strength capabilities while ascending and descending stairs (Hortobágyi et al. 2003). Kamen et al. (1995) and Häkkinen et al. (1998b) proposed that age-related decline in strength may also be due to decreased maximal voluntary activation of the agonist muscle or changes in degree of agonist-antagonist co-activation. Macaluso et al. (2002) have suggested the lower level of muscle strength in older women be explained partly by increased co-activation of the antagonist muscles during knee extension.

For simple movements such as elbow flexion, older people use co-activation to make their movements smoother and increase the accuracy of their movement. Increased co-activity prevents older people to accelerating as rapidly as young people. Older people also co-activate more at moment onset and spend a greater portion of the movement co-activating their muscles as compared to young people. (Seidler-Dobrin et al. 1998.)

3 RATIONALE FOR THE STUDY AND STUDY HYPOTHESES

There are many studies about co-activation in healthy adults and old people during isometric power, force measurements or quiet stance. Only a few studies have been made with EMG measurements of lower limb agonist and antagonist muscles in stair walking. Vertical ground reaction forces (GRF) from force plates have been investigated in level walking and stair walking in young and old people. However, there are only few studies that have used accurate staircases with enough steps to analyse the vertical GRF from force plates. In two studies, EMG and GRF were analysed together, but the studies were from level walking and stair walking in children. Therefore, it would be interesting to determine the degree of co-activation in relation to the vertical GRF in young and old women during stair ascent and descent.

Therefore the hypotheses of this study were that (1) old people employ greater muscular antagonist co-activation than younger people during stair walking, and consequently (2) old people have altered vertical GRF profile during descending and ascending from stairs compared to younger people. Finally, it was hypothesized that (3) old people would show different magnitudes and timing of muscular antagonist co-activation with respect to various vertical GRF phases as compared to young people.

4 MATERIAL AND METHODS

4.1 Subjects

The study is part of a larger intervention study that is being carried out in Odense, Denmark. The subjects for the study included ten healthy, danish, young women and nineteen healthy old women. Subject characteristics and differences between old and young subjects groups are detailed in Table 1. The old subjects had more body fat, less FFM and higher BMI when compared to young subjects. The subjects body fat (%), fat free mass (FFM) and body mass index (BMI) were measured by bioimpedance. All subjects volunteered, were living independently at home, and were engaged in recreational activities for at least one hour per week. Prior to the study, all subjects provided a physician`s approval to participate in the study and completed a medical and physical activity questionnaire to determine their eligibility. Subjects were excluded if they had a history of orthopaedic or neurological disorders, and if they showed bone fractures in the lower extremities within the last 5 years. The testing protocol was performed by all subjects and no subjects withdrew from the study because of an inability to perform the tests. All subjects were informed about the nature, scope and risks of the study, and they signed a consent form before participating. The study was approved by the local ethics committee.

Table 1 Physical characteristics of the old and young subjects

	Old (n19)			Young (n10)			
	Mean	Sd	Range	Mean	Sd	Range	p-value
Age (years)	72,3	6,6	65,0-82,0	25,8	2,0	23,0-29,0	
Weight (kg)	66,1	9,8	48,1-82,7	63,1	7,7	50,1-76,9	.386
Height (cm)	159,0	6,0	149-168	167,0	7,7	162-176	.004
Body fat (%)	36,1	7,1	21,3-46,6	26,1	4,8	17,9-31,6	.001
FFM (kg)	41,8	2,9	36,6-46,6	46,4	3,7	41,1-49,8	.001
BMI (kg/m²)	26,0	4,0	20,5-34	22,6	1,7	19,1-24,8	.003

All tests were performed at the Laboratory of The Institute of Sport Science and Clinical Biomechanics, University of Southern Denmark in the autumn of 2005. The subjects visited the laboratory two times. In the first visit the subjects were familiarized with testing equipment, procedure and environment, and data for the present study was collected. The data from the second visit were used for future analysis. For the tests periods, the subjects were dressed in a shirt and black pantyhose with no shoes. As a warm-up subjects rode a bicycle ergometer at approximately 70 RPM for 5 min at a resistance of 1 Kg.

4.2 Staircase set-up

The wooden staircase included nine steps with railing on the right side and one force plate (Kistler 9281 B, 40 x 60 cm). The force plate was placed on the fifth step, where it recorded the vertical forces generated during stair ascent and descent. The vertical GRF signal (Fz) was collected at 1000 Hz from the Kistler amplifier using a 12-bit A/D converter (DT 3010, Data Transition, Inc). The definition of the various GRF parameters was similar to that reported by Stüssi & Debrunner (1980) and Stacoff et al. (2005). The staircase was designed such that each step was 60 cm wide, with a rise of 16 cm from step to step and depth of steps 23 cm. Each subject had 8 conditions which they had practised during familarization. The conditions for this study were:

* ascent at self selected velocity without handrail starting on left leg (ASV)
* descent at self selected velocity without handrail starting on right leg (DSV)
* ascent at maximum velocity without handrail starting on left leg (AMV)

4.3 Definition and analysis of the vertical GRF

In this study, the parameters of the vertical GRF were adapted after Stüssi and Debrunner (1980) and Stacoff et al. (2005), and the force values were normalized to percentage of body weight (%BW). During the process of analysis, each vertical GRF curve was split into two parts and a maximum was detected both for the left and right side of this midline. This enables definition of the first weight-bearing GRF peak (Fz2) which appears in the phase of weight acceptance after foot touch-down and the second weight-bearing GRF peak (Fz4) which appears in the foot takeoff (Figure 1). The initial GRF impact peak (Fz1) was not detected for the reasons reported by Stacoff et al. (2005). The mid-phase minimum point (Fz3) was also detected and is located between the first peak (Fz2) and the second peak (Fz4). It appears in mid-stance phase during unloading (Stüssi and Debrunner 1980).

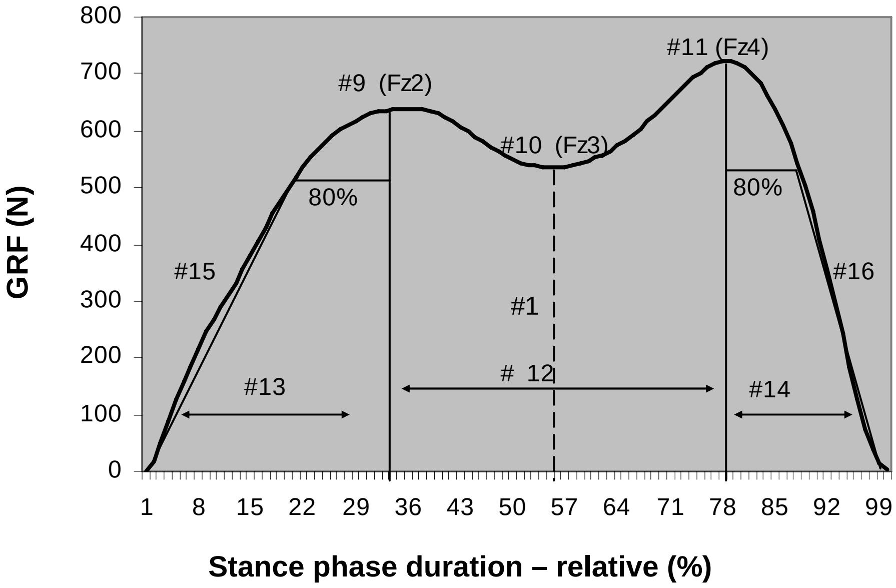

Figure 1 The GRF curve illustrated in absolute units from foot-touch down to foot take-off while ascending the stairs at self selected velocity. The parameters are presented on the figure and below.

#1 Mean values of entire stance phase

#9 Value at the first Fz peak, known as Fz2, GRF (% BW)

#10 Values at Fz mid-phase minimum point, known as Fz3, GRF (% BW)

#11 Values at the second Fz peak, known as Fz4, GRF (% BW)

#12 Mean values in the mid-phase of stance phase, from the first peak to the second peak, GRF (% BW)

#13 Mean values in the first part of the stance phase, from foot touch-down to the first peak (loading phase), GRF (% BW)

#14 Mean values in the final part of the stance phase, from the second peak to foot take-off (unloading phase), GRF (% BW)

#15 Fz loading slope, known as bn, from foot touch-down to 80% of the first peak, ΔGRF/Δtime (NS^{-1} % BW^{-1})

#16 Fz unloading slope, known as en, from 80% of the second peak to foot take-off ΔGRF/Δtime (NS^{-1} % BW^{-1})

The GRF loading slope (ΔGRF/Δtime) during the weight-acceptance phase (bn) and the GRF unloading slope during the weight unloading phase (en) (Stüssi & Debrunner 1980) were also determined. Nigg & Marlock (1987) have reported that those two parameters describe the rate or speed with which GRF force develops in the phases of weight acceptance and unloading, respectively. In accordance with Stacoff et al. (2005) GRF slopes (bn, en) were calculated between the 80% value of the first peak Fz2 and the second peak Fz4, respectively, as depicted in Figure 1 (parameters 15 and 16). The mean GRF value in the entire stance phase, the first part of stance phase, the mid-phase of stance phase and the final part of stance phase also were calculated. From the time analysis the step cycle duration, step frequency, the fractional part of stance phase duration relative to step cycle duration ('duty factor'), time for foot touch-down, time for foot take-off and total stance phase duration were calculated. The selected parameters for step force analysis were described above.

After the collection of the EMG and vertical GRF, the data were analysed using a software programme that was custom-made for this project (Aagaard 2005). The programme analyzed the GRF and EMG signals in the different stair walking situations. Further, a separate custom-made analysis programme (Aagaard 2005) was used to analyze all MVC contractions. A third custom-made analysis programme (Aagaard 2005) was used to determine the magnitude of agonist-antagonist muscle co-activation in the stair walking trials. During the GRF analysis, the programme automatically identified the different parameters of the M -shape GRF curve (cf. Figure 1) in accordance with Stacoff et al. (2005). In AMV with those subjects who showed a single-peak GRF waveform, the profile was analyzed in a way such that the first peak Fz2, the mid-phase minimum point Fz3, and the second peak Fz4 were identified as the one and same point. In DSV with those subjects who showed many smaller peaks after the first highest one, the definition was in a way that after the first peak, the second peak was selected to be the subsequent highest GRF peak from the other smaller peaks. If there was no recognizable second peak, the parameters were defined same way as in AMV, i.e. using a single GRF peak.

4.4 EMG and MVC measurements

EMG activity was measured during stair ascent and descent, and during maximal voluntary contraction (MVC) from eight muscles of the left leg. Those muscles were m. vastus lateralis (VL), m. vastus medialis (VM), m. rectus femoris (RF), m. biceps femoris caput longum (BFcl), m. semitendinosus (ST), m. soleus (Sol), m. gastrocnemius lateral (GasLat) and m. tibialis anterior (TA). EMG signals were recorded by use of custom-made EMG amplifiers using bipolar surface EMG electrodes (Ambu, MedicoTest A/S, type N-00-S). The EMG-system consisted of four EMG-amplifiers, each including two channels and a common reference electrode. Each amplifier therefore required 5 EMG electrodes – two for each channel and one reference. Each channel was using an instrumentation amplifier as the main component at the input stage. Thereafter, the signal was led through circuitry having two main functions, 1) to compensate for a DC offset input and 2) to filter to limit the bandwidth. The amplifiers were in pairs fed from four AA 1.5V batteries. The output signal from each channel was used as 8 single-end inputs into a 32 channels 12-bit A/D-converter (Data Translation Inc, Type DT3010), a part of the Peak Motus (Peak Performance Technologies Inc, 2000 Version) 3D motion analysis system. The A/D-converter was set to gain the EMG input signal by a factor of 8. The electrodes gain was 400 (52dB). The amplifier used a 3-dB bandpass filter with cutoff frequencies of 10 Hz and 550 Hz, respectively, and a signal-to-noise ratio of approximately exceeding 55 dB. The max signal output amplitude was 3.6 Vpp. Before placing the electrode pairs the skin was shaved and cleaned by alcohol to increase conductivity and to reduce electrode-skin impedance. The signals of EMG and GRF were recorded synchronously.

MVC of the lower limbs was measured three consecutive times during isometric contractions. The mean EMG activation of the measured parameters was as a fraction of the EMG measured at isometric maximal voluntary contraction from eight muscles. The best performance trial was used as the maximal EMG activity. Subjects were instructed to exert their maximal force as fast as possible during a period of 4 s. To support the maximal effort, a strong verbal encouragement was given to each three consecutive contractions. The MVC for the hamstrings and quadriceps muscles were performed in a sitting position with a flexion of 120 degrees of the knee and for the plantar flexion of 45. Also the MVC of Sol and GasLat were performed in a sitting position during maximal isometric plantar flexion. TA activation was recorded in a standing position with a maximal isometric dorsi flexion of the ankle.

The muscle co-activation was analysed in an x-y diagram. The x-axis showing the time in ms and the y-axis showing the muscle activation in % of the maximal EMG output of the measured muscles. The co-activation was analysed from the thigh muscles VL+VM+RF (agonist) and BFcl+ST (antagonist) and from the calf muscles Sol+GasLat (agonist) and TA (antagonist). The co-activation between the muscles was analysed for all the different parameters of the vertical GRF curve (Figure 1). The co-activation was calculated by Larsen et al. (2006):

$$\%Coactivity = 2 \times \frac{common\ area\ \ Antagonist\ \&\ Agonist}{area\ \ Antagonist + area\ \ Agonist} \times 100\%$$

4.5 Statistical analysis

GRF parameters normalized to percent of body mass, EMG normalized to percent of MVC activation from eight leg muscles, and muscular antagonist co-activation and time analyse parameters were compared between young and old subjects groups by an unpaired two-tailed *t*-test. An analysis of covariance (ANCOVA) was used to investigate the effect of step cycle duration on the mean GRF values of the entire stance phase, the first peak, the mid-phase minimum point, the second peak, and the loading and unloading slopes. Relationships between the step cycle duration, stance phase duration and GRF parameters normalized to body mass were studied using Pearson correlation analysis (r). The linear regression was used to examine the relation of the mean GRF values of the entire stance phase and step cycle duration. The SPSS 11.5 was used to perform all statistical analysis. The level of significance was set at $p < 0.05$.

5 RESULTS

The results showed old subjects to be slower, their step cycle duration and stance phase to be longer when compared to young subjects (Table 2). Also, the relative stance phase duration (% step cycle) was longer in old subjects in AMV and ASV.

Table 2 Results from step cycle measures in old and young subjects

		Step frequency (Hz)	Step cycle duration (ms)	Complete stance phase duration (ms)	Stance phase duration / step cycle duration (%)
	AMV	1,3 (0,3)	850,1 (250,1)	512,0 (160,8)	60,1 (7,1)
OLD	ASV	0,8 (0,2)	1254,3 (250,1)	852,8 (189,3)	68,0 (5,2)
	DSV	0,9 (0,3)	1206,6 (536,5)	783,0 (384,0)	65,0 (3,7)
	AMV	2,1(0,3)***	476,4 (51,74)***	227,4 (24,1)***	47,8 (2,3)***
YOUNG	ASV	1,0 (0,1)**	1007,3 (122,1)***	658,2 (69,6)***	65,5 (2,3)
	DSV	1,2 (0,2)**	878,9 (158,7)	579,1 (122,0)	65,5 (3,3)

***, ** Significant differ from the value of old subjects

5.1 Stair ascent at maximum velocity (AMV)

5.1.1 Vertical GRF

The absolute vertical GRF curves showed different shapes between old and young subjects. In ascending the stairs at maximum velocity the vertical GRF profiles were characterized by a double or a single waveform. The profile with a single waveform was dominant in both old, 14 subjects of the 19 and all the young subjects. The mean GRF curves of the old and young subjects (Figure 2) and the individual variation within the old (Figure 3) and young subjects (Figure 4) show different profiles of GRFs. When the vertical GRF is normalized to body mass, the young subjects had significantly higher values in all force parameters compared to the old subjects (Appendix 1). When the step cycle duration was used as a covariate, significant differences ($p < .001$) between old and young subjects diminished ($p < 0.01$) in the first peak and mid stance phase (Appendix 11). The time parameters established old subjects to be slower. They had a longer step cycle duration and stance phase, and slower step frequency than young subjects. (Appendix 2).

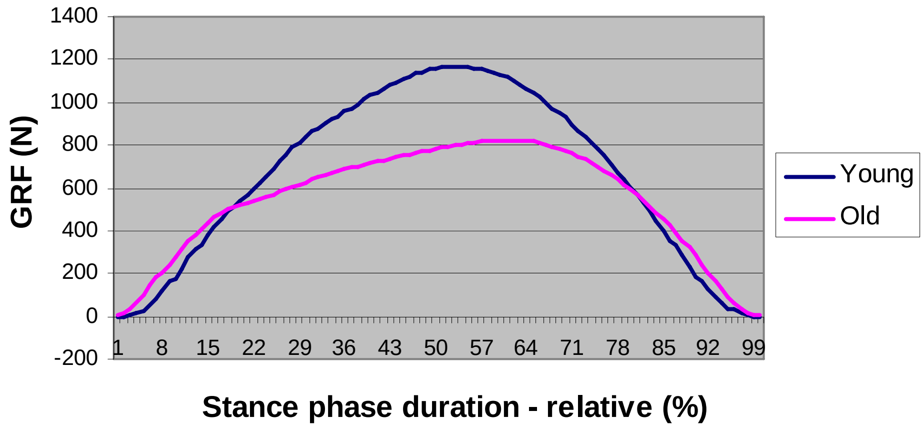

Figure 2 Mean vertical GRF curve from foot touch-down to foot take-off in young and old women during stair ascent at maximum velocity. All parameters (Figure 1) between old and young subjects were $p < 0.001$.

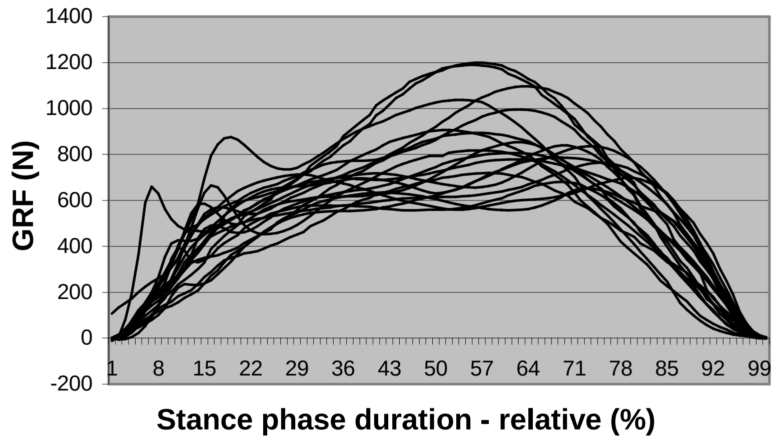

Figure 3 Individual variation in vertical GRF curves from foot touch-down to foot take-off in old women during stair ascent at maximum velocity.

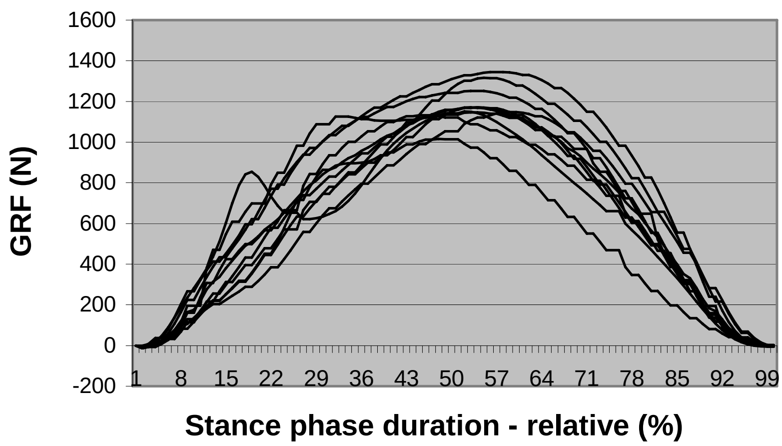

Figure 4 Individual variation in vertical GRF curves from foot touch-down to foot take-off in young women during stair ascent at maximum velocity.

5.1.2 Muscle antagonist co-activation

For the thigh muscles VL+VM+RF and BFcl+ST, antagonist co-activation was elevated in the elderly for the entire stance phase and loading slope (Figure 5). The calf muscle combination Sol+GasLat and TA were not significantly different between the old and young subjects (Appendix 3).

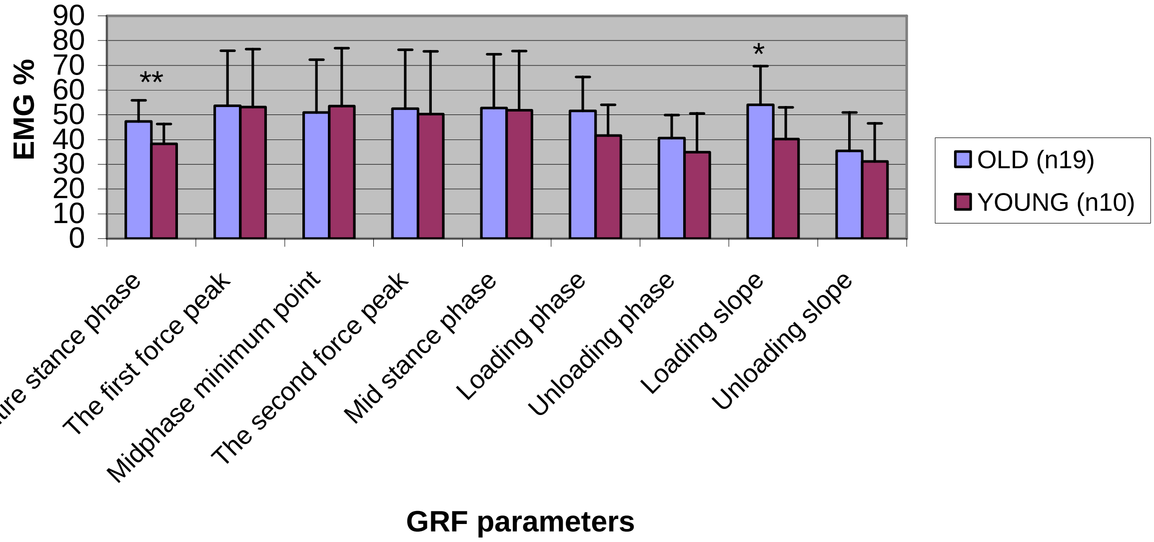

Figure 5 Antagonist co-activation determined from the relative EMG activity from the muscle groups VL+VM+RF and BFcl+ST during stair ascent at maximum velocity in old and young subjects. * $p < 0.05$, ** $p < 0.01$.

5.1.3 EMG normalized to maximal MVC muscle activation

Absolute muscle EMG activation and vertical GRF curve for one old and one young subject are displayed together in Appendix 4. Old subjects showed relatively higher normalized EMG-signals (% of MVC-signal) at the VL (Figure 6) and at the VM in the second peak, and in the loading and unloading phases. Young subjects showed higher EMG activity at the TA (Figure 7), at the GasLat in the entire stance phase, the loading phase and the loading slope, and Sol in the entire stance phase, the first peak, the mid-phase minimum point, the loading phase and the loading slope. No significant differences between the groups were found in the RF, BFcl and ST. (Appendix 5).

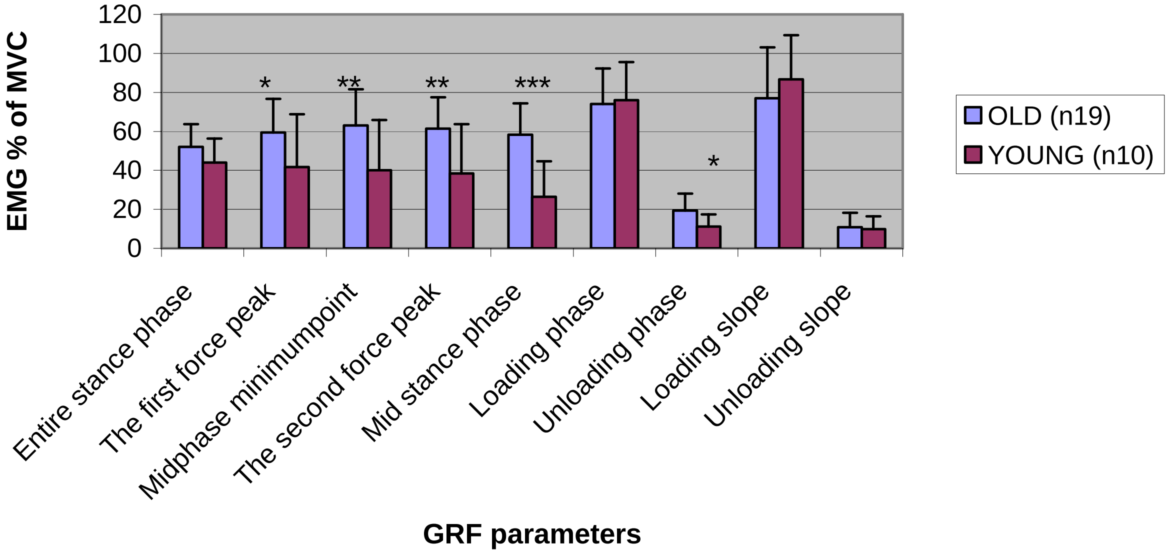

Figure 6 VL muscle activation (normalized to knee extensor MVC) in old and young subjects during stair ascent at maximum velocity. * p < 0.05, ** p < 0.01, *** p < 0.001.

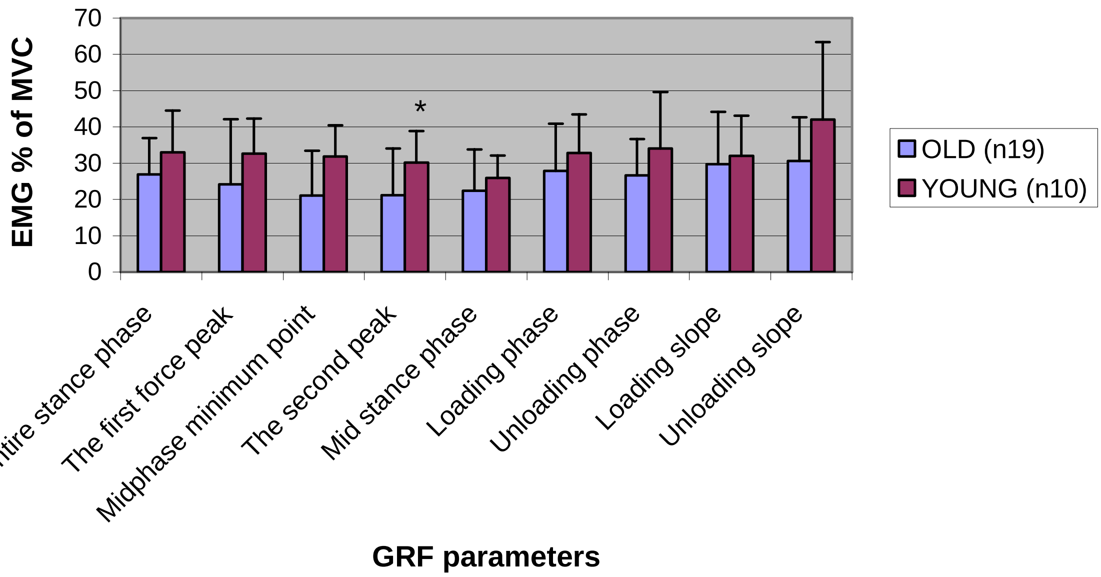

Figure 7 TA muscle activation (normalized to ankle flexor MVC) in old and young subjects during stair ascent at maximum velocity. * p < 0.05.

5.2 Stair ascent at self selected velocity (ASV)

5.2.1 Vertical GRF

The normalized GRF curves showed significantly higher values for old subjects in the mid-phase minimum point and for young subjects in the first peak, and in the loading and unloading slopes. (Appendix 1). When the step cycle duration was used as a covariate, the entire stance phase and loading and unloading slope become significantly different between old and young subjects. The difference in mid stance phase between the groups disappeared as an effect of covariate. (Appendix 11). The absolute vertical GRF profiles showed a double waveform with two unequal peaks, the second being always greater than the first one. For one old subject there was a single waveform profile. The variation between old and young subjects (Figure 8) and the variations within the old (Figure 9) and young subjects (Figure 10) showed differences in GRF profiles. One person did not reach zero which must have been an error in the measurement. At time parameters the old subjects were slower, their step cycle duration was longer, step frequency was slower and their complete stance phase was longer than in young subjects (Appendix 2).

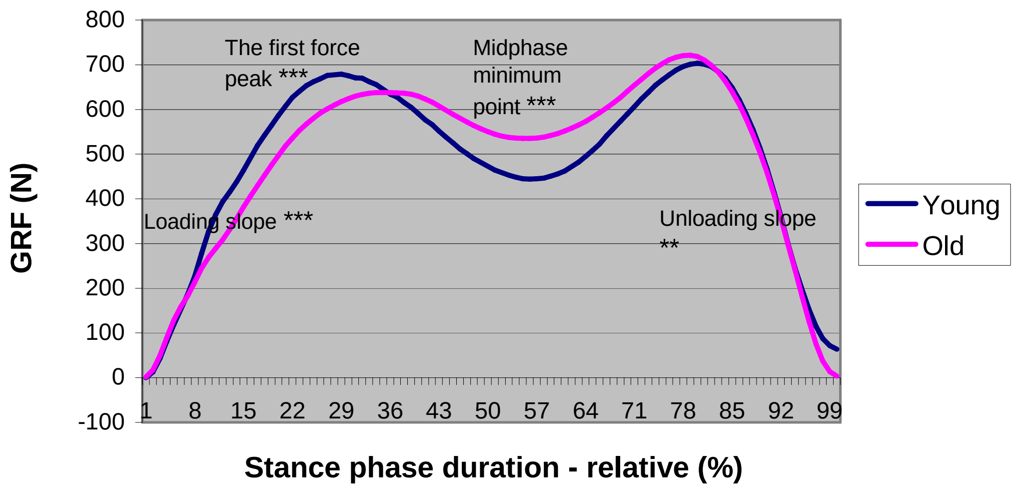

Figure 8 Mean vertical GRF curve from foot touch-down to foot take-off in young and old women during stair ascent at self selected velocity. The differences between old and young subjects were $p < 0.01$**, $p < 0.001$***.

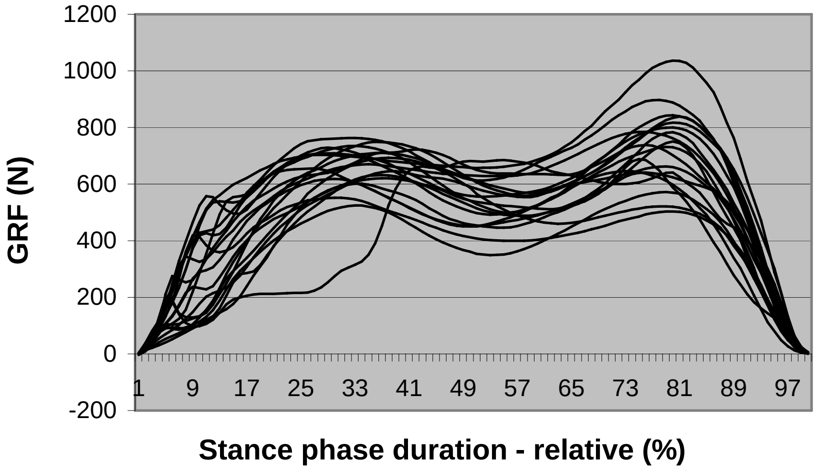

Figure 9 Individual vertical GRF curves from foot touch-down to foot take-off in old women during stair ascent at self selected velocity.

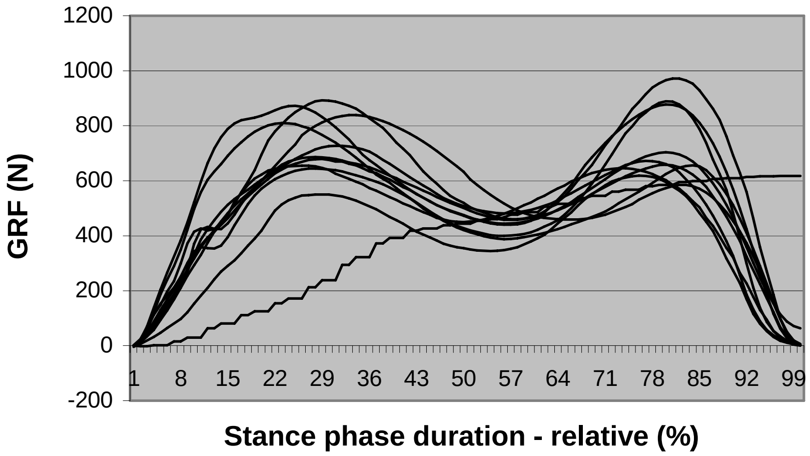

Figure 10 Individual vertical GRF curves from foot touch-down to foot take-off in young women during stair ascent at self selected velocity.

5.2.2 Antagonist muscle co-activation

The thigh muscle groups VL+VM+RF and BFcl+ST showed higher co-activation in entire stance phase and mid stance phase for old subjects (Figure 11). In the Sol+GasLat and TA calf muscle groups (Figure 12), the first peak showed higher co-activation for the old subjects and unloading phase showed higher co-activation for the young subjects (Appendix 3).

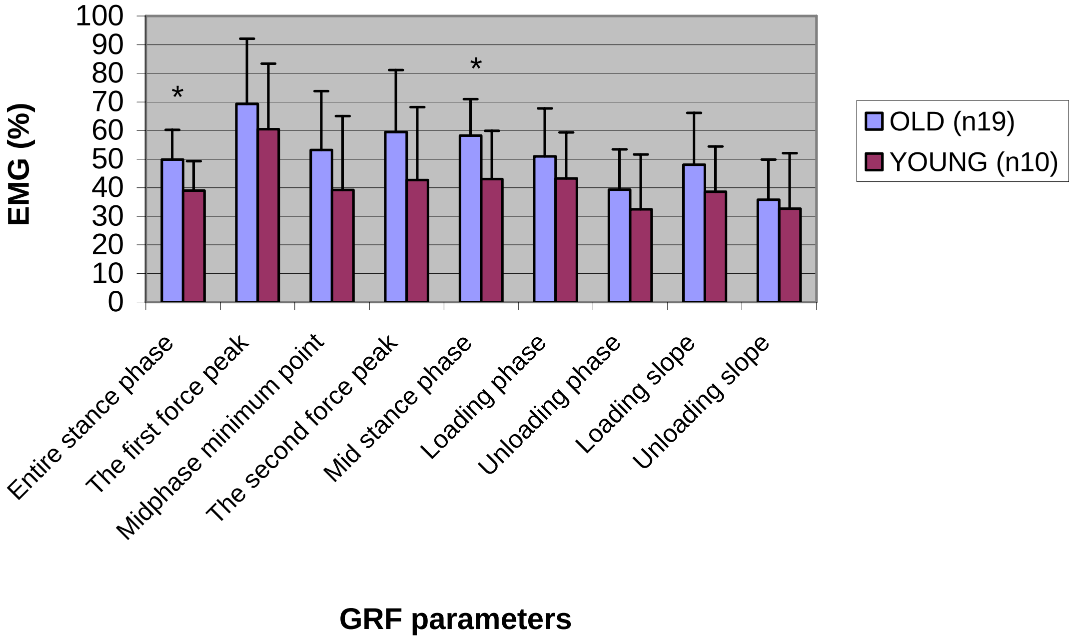

Figure 11 Antagonist co-activation determined from the relative EMG activity from the muscle groups VL+VM+RF and BFcl+ST during stair ascent at self selected velocity in old and young subjects. * p < 0.05.

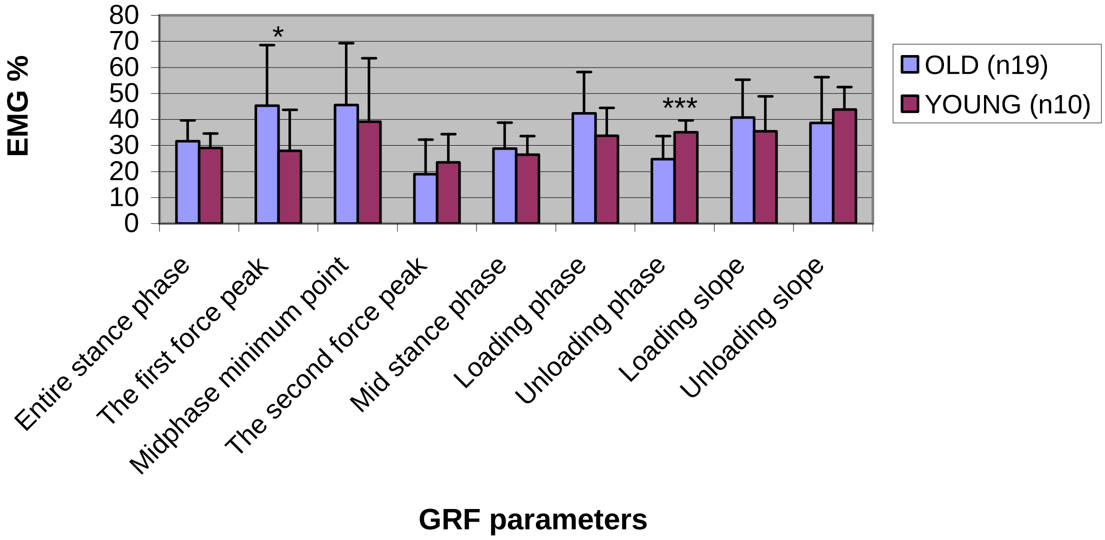

Figure 12 Antagonist co-activation determined from the relative EMG activity from the muscle groups Sol+GasLat and TA during stair ascent at self selected velocity in old and young subjects. * p < 0.05, *** p < 0.001.

5.2.3 EMG normalized to maximum MVC muscle activation

Absolute muscle EMG activation and the vertical GRF curve for one old and one young subject during ASV are displayed together in Appendix 6. Normalized EMG muscle activation (% of MVC-signal) showed significant differences in all muscles. Old subjects had significantly higher values nearly in all parameters in the VL (Figure 13), BFcl (Figure 14), VM, RF, and ST. Also, at the TA (Figure 15), GasLat and Sol, the old subjects had higher values in some parameters compared to the young subjects. (Appendix 7.)

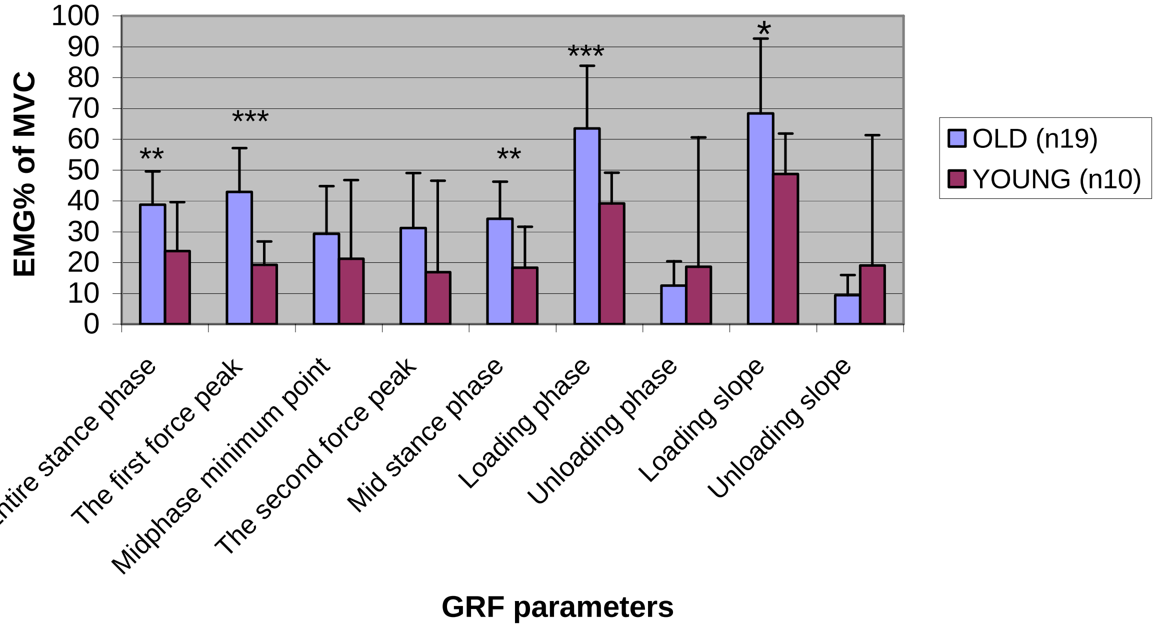

Figure 13 VL muscle activation (normalized to knee extensor MVC) in old and young subjects during stair ascent at self selected velocity. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

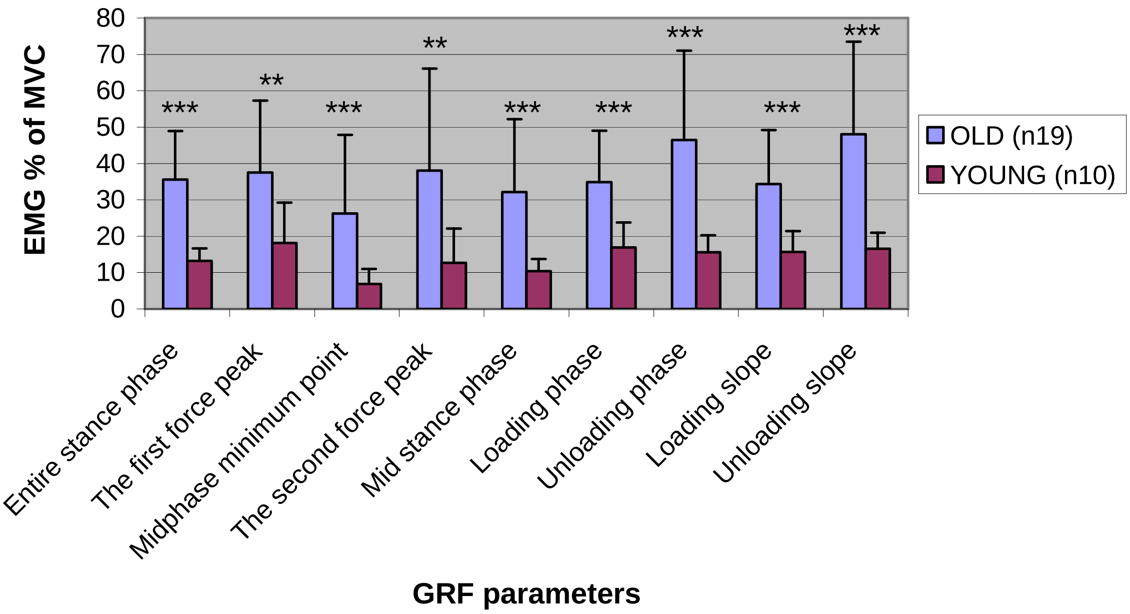

Figure 14 BFcl muscle activation (normalized to knee flexor MVC) in old and young subjects during stair ascent at self selected velocity. ** $p < 0.01$, *** $p < 0.001$.

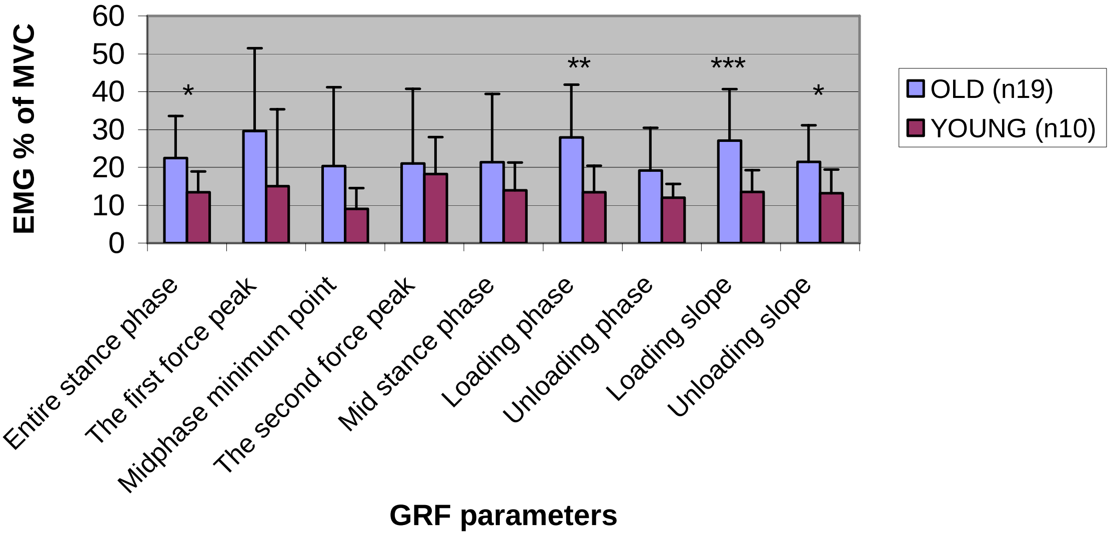

Figure 15 TA muscle activation (normalized to ankle flexor MVC) in old and young subjects during stair ascent at self selected velocity. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

5.3 Stair descent at self selected velocity (DSV)

5.3.1 Vertical GRF

The normalized vertical GRF was significantly different between old and young subjects. The entire stance phase and the unloading phase were higher for old subjects, and the loading phase and the unloading slope were higher for the young subjects (Appendix 1). When the step cycle duration was used as a covariate, the significant differences between old and young subjects disappeared in the entire stance phase, unloading slope, and loading and unloading phases. However, the first peak and loading slope become significantly different between the groups. (Appendix 11). At the profile of absolute vertical GRF curve, the typical double waveform was no longer present. After the first maximum, the curves progressed in large variations; 12 of the 19 old subjects and 8 of the 10 young subjects showed a recognizable second peak while the rest showed only a one peak. The dominant profile was with the first maximum peak following several smaller peaks and one slightly higher peak as the second peak. The differences between old and young subjects are seen in Figure 16. The variation within the old subjects is seen in Figure 17 and the variation within young subjects in Figure 18. Time analysis showed old subjects to have a slower step frequency as compared to young subjects (Appendix 2).

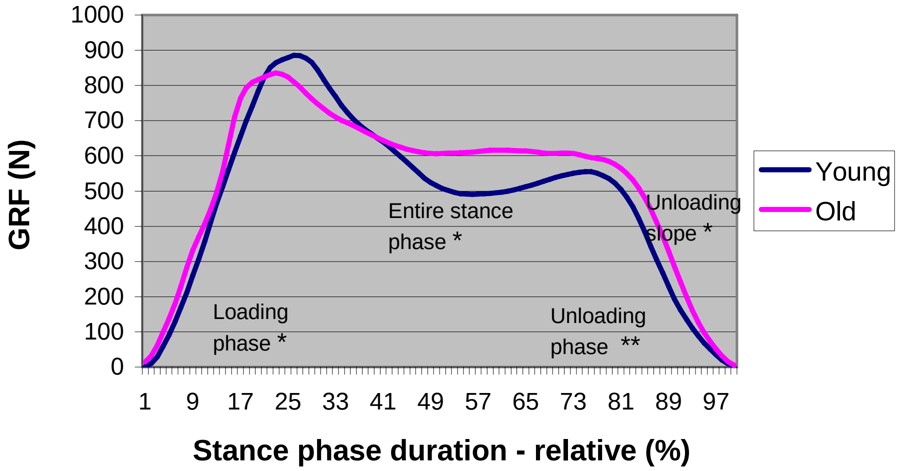

Figure 16 Mean vertical GRF curve from foot touch-down to foot take-off in young and old women during stair descent at self selected velocity. The differences between old and young subjects were * $p < 0.05$, ** $p < 0.01$.

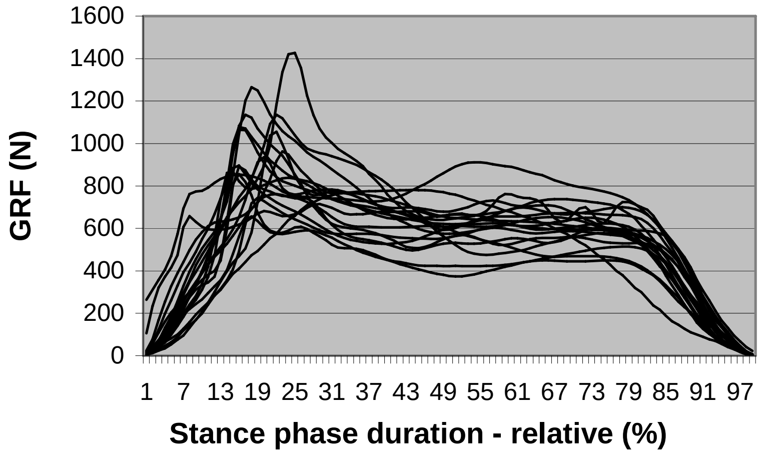

Figure 17 Individual variation in vertical GRF curves from foot touch-down to foot take-off in old women during stair descent at self selected velocity.

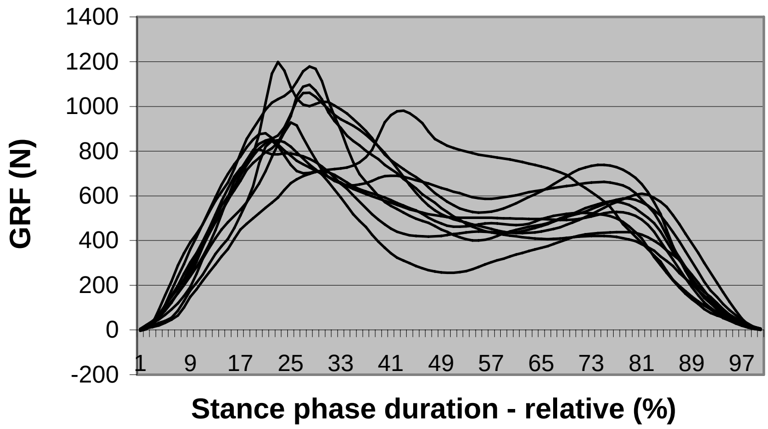

Figure 18 Individual variation in vertical GRF curves from foot touch-down to foot take-off in young women during stair descent at self selected velocity.

5.3.2 Antagonist muscle co-activation

The old subjects had higher co-activation during the entire stance phase, first peak, loading phase, and loading slope in the thigh muscle groups VL+VM+RF and BFcl+ST (Figure 19). The young subjects had a higher second peak in the calf muscle groups Sol+Gaslat and TA. (Appendix 3.)

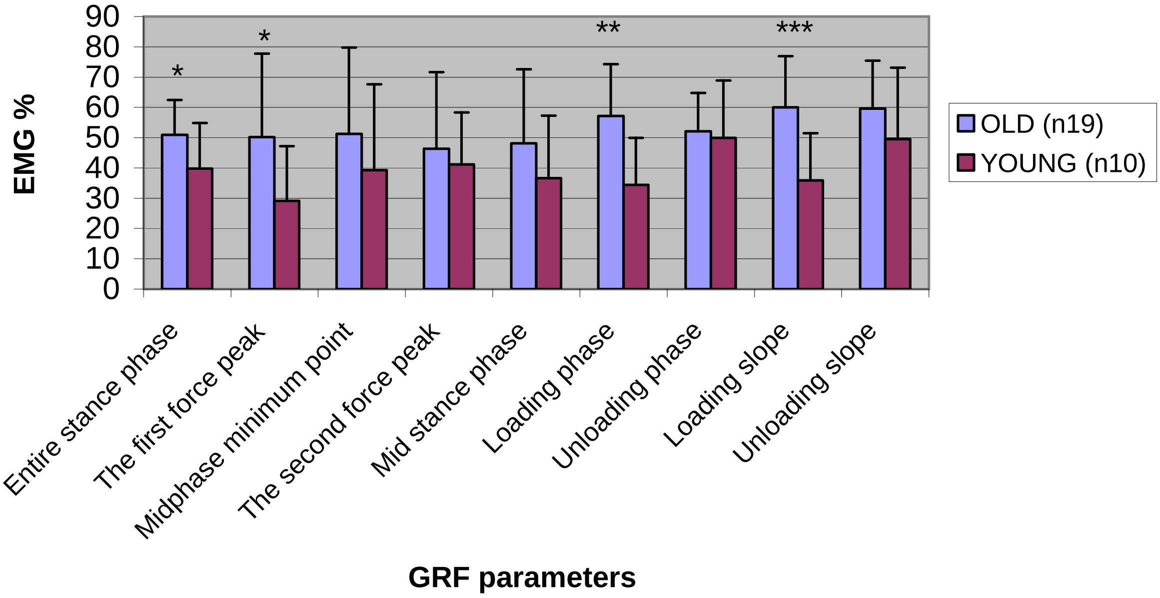

Figure 19 Antagonist co-activation determined from the relative EMG activity from the muscle groups VL+VM+RF and BFcl+ST during stair descent at self selected velocity in old and young subjects. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

5.3.3 EMG normalized to maximum MVC muscle activation

Absolute muscles EMG activation and the vertical GRF curve for one old and one young subject during DSV are displayed together in Appendix 8. There was significantly higher normalized EMG activity (% of MVC-signal) for old subjects in the VL (Figure 20), BFcl (Figure 21), TA (Figure 22), and all other muscles, except Gaslat. (Appendix 9.)

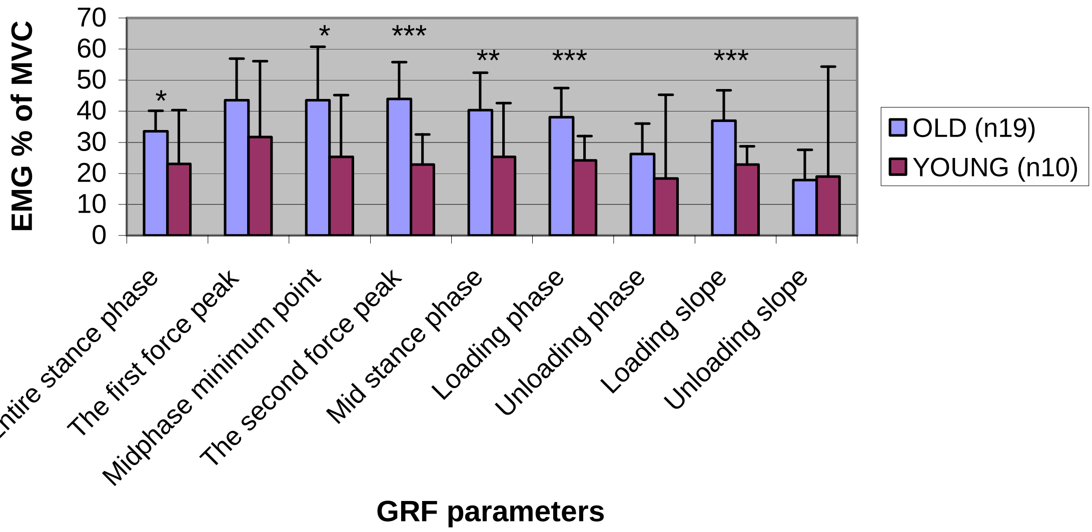

Figure 20 VL muscle activation (normalized to knee extensor MVC) in old and young subjects during stair descent at self selected velocity. * p < 0.05, ** p < 0.01, *** p < 0.001.

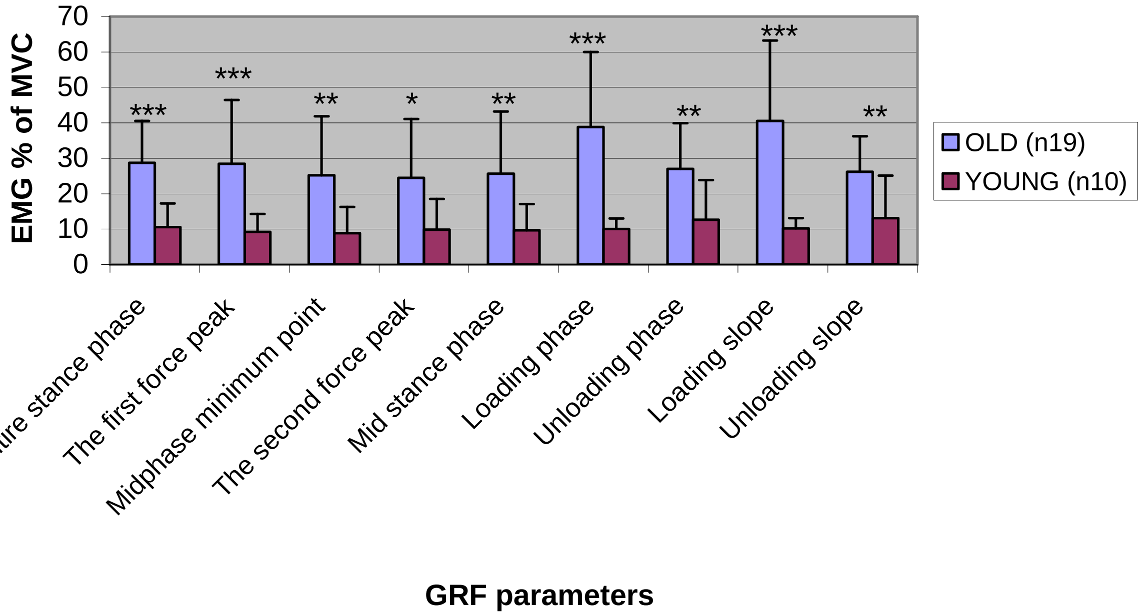

Figure 21 BFcl muscle activation (normalized to knee flexor MVC) in old and young subjects during stair descent at self selected velocity. * p < 0.05, ** p < 0.01, *** p < 0.001.

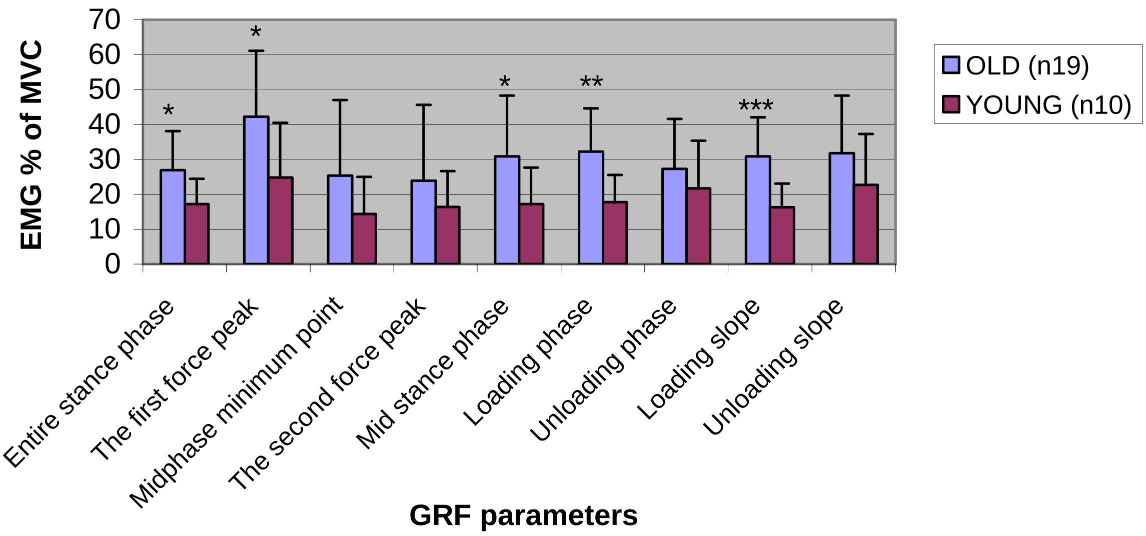

Figure 22 TA muscle activation (normalized to ankle flexor MVC) in old and young subjects during stair descent at self selected velocity. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

5.4 Correlation between vertical GRF parameters and time parameters of step cycle

The normalized GRF parameters correlated with the duration of the step cycle and complete stance phase mainly in old subjects. Long step cycle duration was associated with low force values, a low entire stance phase, and long unloading slope in old subjects. A similar result was obtained in the young subjects at the loading slope. The results for the complete stance phase duration were in same direction as for step cycle duration. (Appendix 10.) The mean GRF in the entire stance phase was associated with step cycle duration ($p < .001$) in old subjects (Figure 23). For young subjects no significant result were found ($R^2 = .024$, $y = 101.04 + .013x$, $p = .671$).

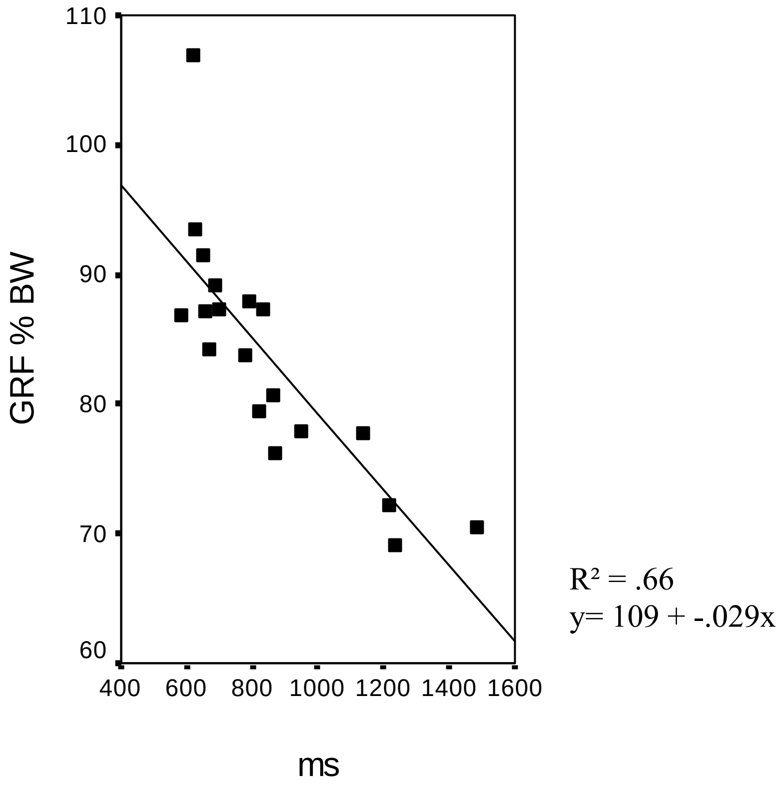

Figure 23 Linear regression between the mean GRF in the entire stance phase and step cycle duration in old subjects during stair ascent at maximum velocity.

During ASV, the correlations showed similar results than in AMV for the old subjects. For the young subjects, the long complete stance phase duration was associated with a small entire stance phase and low loading slope. (Appendix 10.) The mean GRF in the entire stance phase was associated to the step cycle duration ($p < .001$) in old subjects (Figure 24). For young subjects there was no significant relationship ($R^2 = .241$, $y = 91.69 + -.012x$, $p = .149$).

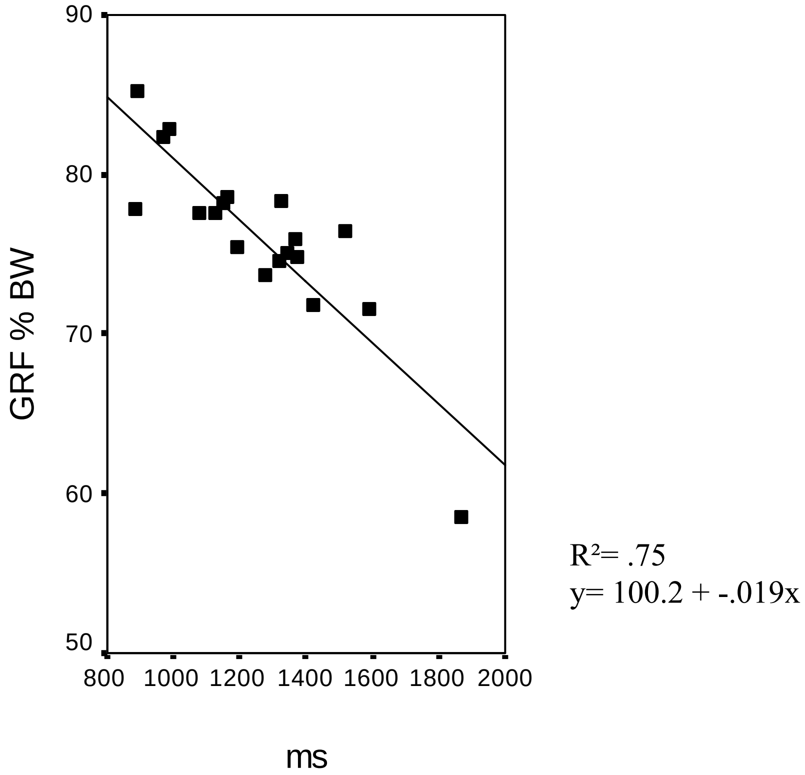

Figure 24 Linear regression between the mean GRF in the entire stance phase and step cycle duration in old subjects during stair ascent at self selected velocity.

During DSV, the correlations showed the first peak and the loading slope to be higher when the step cycle duration was long for the old subjects,. When the complete stance phase was long, the first peak and the loading slope were lower. In young subjects, the slow step cycle duration was associated to a high entire stance phase and a high second peak. Long complete stance phase duration was associated to a low entire stance phase, a high first peak and a low second peak, a mid-phase minimum point, and an unloading phase in young subjects. (Appendix 11.) The mean GRF in the entire stance phase was not associated to step cycle duration in old subjects (R^2 = .015, y= 82.51 + .001x, p = .621). For the young subjects, the relationship was less evident (R^2 = .399, y= 90.78 + .014x, p = .050).

6 DISCUSSION

The purpose of this study was to investigate the differences in muscular antagonist co-activation and the shape of vertical GRF during ascending and descending the stairs between old and young subjects, and to evaluate the differences in old and young subject´s leg muscle co-activation related to vertical ground reaction force (GRF). The results of this study demonstrate that old subjects have higher co-activation in thigh muscles related to vertical GRF when ascending the stairs at maximum velocity (AMV), when ascending the stairs at self selected velocity (ASV), and when descending the stairs at self selected velocity (DSV). The results showed three different dominant profiles for each of the measured conditions; AMV, ASV and DSV. The profile of the vertical GRF was different between old and young subjects during ascent and descent of the stairs when looking at the figures and parameters. Also the muscle activation was different in old and young subjects in AMV, ASV and DSV.

6.1 Vertical GRF curve

Surprisingly at AMV, the dominant profile was a one peak waveform for both old subjects and young subjects. One explanation for differences in vertical GRF profile while AMV might be that when the subjects ascend at maximal velocity, the time parameters of the step cycle were faster than at self selected velocity in both old and young subject groups (Appendix 2). This may result in one peak waveform profile of the vertical GRF. Alexander (1984) has reported that during running the vertical GRF showed only a single peak waveform which he explained to be a consequence of faster velocity compared to walking. From that supposition, the one peak of AMV can be explained by the faster velocity than at the ASV in which the double waveform was dominant. It might be that during AMV, the subjects actually run up the stairs while they were asked to ascend at their maximal velocity.

As expected, the shape of vertical GRF curves showed a double waveform as a dominant profile for both old and young subjects groups while ascending the stairs at self selected velocity (ASV). The results are similar to other studies made by Stacoff et al. (2005), Christina & Cavanagh (2000) and Riener et al. (2002). As predicted, the profiles between the old and young subjects differ. The first peak, the loading, and the unloading slopes were significantly higher with young subjects which agree with Stacoff et al. (2005) study. They found age to be a factor in stair walking in that young subjects were faster and produced a larger vertical GRF maximum during stair ascent when compared to old subjects (Stacoff et al. 2005). In this study, the mid-phase minimum point was significantly higher for the old subjects group which was not reported earlier. When looking at the time parameters of a step cycle, the old subjects used slower velocity than young subjects. The old subjects` decreased muscle force production (Häkkinen 1998b, Vandervoort 2001) may be related to slower velocity.

The results from DSV were as expected. While descending the stairs, the vertical GRF curves established the variation that also Stacoff et al. (2005) found. Christina & Cavanagh (2002), Riener et al. (2002), Savvidis & von der Decken (1999) and Lobo da Costa & Amadio (1995) have not reported any variations from a double waveform while descending a set of stairs. At the present study, after the maximum first peak there were either many smaller peaks or the second peak, which Stacoff et al. (2005) findings also confirm. The entire stance phase and unloading phase were higher for old subjects, and loading phase and the unloading slope were higher for young subjects. Christina & Cavanagh (2002) reported the loading slope to be different between old and young subjects, which was not found in this study. Stacoff et al. (2005) found no age effect on stair descent parameters that they used, which differ from the present study.

For the old subjects there were a smaller reserve capacity when compared to young subjects by means of elevated EMG activation and the ratio of GRF during ASV and AMV. The force ratio was nearly same for old subjects during ASV and AMV.

6.2 EMG activation and co-activation

The findings of muscle EMG activation in old and young subjects during MVC, showed young subjects to have higher values in all force parameters in vertical GRF curve at AMV, which is associated with the different profile of the vertical GRF between old and young subjects. As mentioned earlier, the young subjects were faster than old subjects in regard to the time parameters. Winter (1984) has showed that an increase in speed is closely linked to higher EMG levels. The young subjects had higher values in GasLat and Sol which might be an effect of knee or ankle strategy while ascending the stairs. The co-activation findings support the idea of a hip strategy for old subjects because co-activation was significantly higher at the thigh muscles. Manchester et al. (1989) have reported that old people tend to use a hip strategy while keeping balance on a movable platform compared to young people.

As found by James & Parker (1989), ASV muscle activity (% of MVC-signal) showed differences between old and young subjects´ muscle activity during stair walking at own velocity. When descending the stairs, the muscle activity was higher for old subjects compared to young subjects in all muscles. The results showed that old subjects were nearer to their maximal capacity. Old subjects may need to activate more muscles to control postural balance during dynamic balance or motor tasks. Patla et al. (1992) have studied different kinds of balance tests in healthy fit elderly people. Movement time, reaction time, weight transfer time, peak force, and rate of change of force were increased in the old subject´s.

In the present study, the old subjects had a higher muscular co-activation in the thigh muscles compared to young subjects in all measured conditions such as AMV, ASV, and DSV. Hortobágyi & De Vita (2000) study is parallel to the findings of DSV. They reported higher co-activity in the older subjects, while descending, to be associated with the pre-activity of the muscles before touch down. The different profiles between old and young subjects might come from a safer walking strategy which older subjects adopt (Simoneau & Cavanagh 1991, Christina & Cavanagh 2000), or old subjects weaker muscle strength (Vandervoort 2001).

Hortobágyi & De Vita (2000) have reported that the altered movement strategy may be a result of greater leg stiffness in the aged. They found that the older subjects had 64% greater leg stiffness during downward stepping than young subjects, and that the increased leg stiffness especially in the old subjects is related to the higher co-activation. As Manchester et al. (1989) have stated, the increased leg stiffness, which comes from higher co-activity in the aged, is a compensatory mechanism driven by the risks and fears associated with the motor challenge. Kamen et al. (1995) studied motor unit discharge behaviour in older people during maximal-effort contractions, and their results demonstrate that maximal motor unit discharge rates are reduced with increasing age. They also suggested that age-related changes in maximal neural activation and strength may vary among the different muscles in relation to their use in daily physical activities.

Winter et al. (1990) have reported significant differences between old and young subjects during level walking. In old people those differences were shorter stride length, longer percent stance time, lower mechanical work done by their plantarflexors at push-off, more flat-footed landing, reduced walking velocity, higher horizontal acceleration of the head at the level of the vestibular system and higher heel horizontal velocity at the instant of heel contact. Winter & Eng (1995) explained that higher horizontal head acceleration and higher heel velocity at heel contact indicates that the head which is the platform for the visual system, is less stable in old people and can increase the risk of losing balance. They also stated that all those differences described by Winter et al. (1990) can be explained as adaptations for a safer walking pattern.

6.3 Correlations

The correlations were made to find out how the GRF parameters are associated with time parameters of step cycle in old and young subjects. The different results between old and young subjects from the correlation analysis and linear regression are associated with the differences in vertical GRF profile. (Appendix 15). Those differences might be related to the different usage of the muscles or the velocity of movement. The co-activation may explain the significant negative correlations observed between step cycle duration and force parameters while ascent at maximal velocity for old subjects. The magnitude the co-activation can increase with age especially during explosive movements which require rapid activation of the agonist muscles (Häkkinen 1998b).

The small number of significant correlations during DSV may be associted with the vertical GRF profile variation. The curves did not show a single dominant profile but a large amount of variation. This variation might affect the correlations since the intra-subject variation in force parameters was large. As predicted, the step cycle duration was a significant covariate for the measured parameters at AMV and ASV. The step cycle duration influences the profile of vertical GRF. The differences between old and young subjects could be explained by step cycle duration which was different between them.

6.4 Critique and suggestions for future study

The present study was made of a sample size (N=29) which was larger enough to explore the hypothesis. DeVita & Bates (1988) suggested that in the analysis of human locomotion using GRFs, a sample size of 25 is indicated. They found the GRF to be reliable, but a minimum

sample size of 18 to 23 was required to produce stable anteriorposterior, vertical, and mediolateral measures. They also noticed that even with an appropriate sample size, some of the observed differences between tested conditions were due to normal performance variability. However, Stacoff et al. (2005) demonstrated trial to trial variability for stair walking to be acceptable for old subjects.
It is possible that the electrodes did not gather all muscle activity that the muscles generated. There was one subject whose EMG signal to noise ratio was not satisfactory and she was deleted before the analysis. The present study investigated the GRF from only one force plate which was on the fifth step on ascent. There could have been another force plate for the supportive leg or the stance leg on a different step as done by Christina & Cavanagh (2002). They found that the GRF was different depending on the step place on the staircase. The present study used a KISTLER force plate which Bobbert & Schamhardt (1990) have found to measure vertical GRF quite accurately. Future research might investigate the vertical GRF profile and muscle activation and co-activation differences between the different stairs during ascent and descent.

Cross-talk of myoelectric signals between neighbouring muscles may affect the results. Cross-talk of approximately 5 to 15% can occur when bipolar surface electrodes are used (De Luca & Merletti 1988). Hortobágyi & De Vita (2000) explained cross-talk to be volume conduction of neural activity from agonist muscles to remote muscles, including the antagonist muscles. They pointed out that cross-talk could artificially augment antagonist muscle co-activity. Aagaard et al. (2000) found 6% of cross-talk between VL-Bfcl and 4% between VM-ST. The cross talk might affect the absolute magnitudes of signals recorded. However, it is possible that it did not influence the age-effects found since similar recording and processing techniques were used for all subjects.

Velocity was not measured in the present study. However, the results from time analysis showed young subjects to have a faster step cycle duration and step frequency. The old subjects have been found to ascend and descend at a slower speed than young subjects (Stacoff et al. 2005). For level walking, the ground reaction forces have been found to be dependent on the gait velocity (Andriacchi et al. 1977). Stacoff et al. (2005) have observed that the gait velocity drops significantly from level walking to stair ascent and descent. They found that the inclination of the stairs was connect to the velocity; the steeper stairs resulted in a slower velocity and longer stance time.

The visual capacity was not compared between old and young subjects in this study. It is possible that the old subjects had a decreased visual capacity as compared to young subjects, which might have influnced the ascent and descent strategies. Simoneu et al. (1991) found that degraded visual acuity has a significant effect on cadence, foot placement and foot clearance. For older people, the reliance on visual input is accompanied by a greater dependence on the increased contraction of muscles and increased amount of co-activation around distal joints (Benjuya et al. 2004). The postural stability is optimal around the ages of 30 to 60 years, and vision is most important for postural stability in older people (Hytönen et al. 1993). Archea (1985) suggested that there are strong interactions between the visual capabilities of older people and the visual qualities of stair treads and other parts of the stair environment to the performance of older people on stairs.

In this study the old subjects had a larger variation within their group than young subjects in almost all measured parameters, which shows the individual differences. When people grow older, they become more different from each other and the variations become larger. As Spirduso (1995, 3) has stated, all persons age at their own speed and the ageing changes progress at own speed. In the present study, the age range of old subjects was wide, the youngest being 65 years old and the oldest, 82 years old. That may be associated with the large variability in different parameters within the old subject group as compared to young subjects.

The muscle strength differences between old and young subjects might effect the differences in the vertical GRF profile and muscle co-activation. Rantanen et al. (1998) have reported a muscle strength decrease of, on average, 1% per year from mid-life on, with the decline accelerating in the higher ages. Healthy people in their 70`s and 80´s score 20-40% lower on a test of isometric strength than young adults, and the very old showed a 50% reduction (Vandervoort 2002). During ascent and descent of the stairs, the old subjects are closer to their maximal muscle capacity. The level of effort needed to execute a task (stair walking) as a percentage of the available maximal capacity is higher for old subjects. (Hortobágyi et al. 2003.) In a future study the age gap should be narrower, or the research should be made with the old and very old subjects in separate groups. This is because muscle activation patterns change with age and older people are using higher co-activity of the lower extremity muscles to get through the voluntary movements (Häkkinen et al. 1998a, Hortobágyi & De Vita 2000, Macaluso et al. 2002).

The results of this study can be generalized because the differences between old and young subjects were clear and significant. However, larger research with more subjects is necessary. With more subjects, the same measures could elucidate the results of the vertical GRF profile from AMV (one peak waveform) and DSV (large variation in waveforms) for older women. The earlier studies by Stacoff et al. (2005) and Christina & Cavanagh (2002) have studied GRF with old men and women mixed into one group. It should be noted that the results obtained in the present study are based on female subjects. Future research could be directed towards the examination of gender differences in vertical GRF and muscular antagonist co-activation, as Bassey et al. (1992) have discovered that on average, women have only half the power of men in leg extensor power test. Also, women had reduced mechanical muscle performance during concentric contraction (Caserotti et al. 2001). These findings lead one to think that the results from the vertical GRF related to co-activation might be different when comparing old men and women. Future research could also examine the differences between young and old men.

This study was part of a larger intervention study. The intervention study is focused on strength training and its effect of co-activation on GRF. In the future, it might be interesting to see how different kinds of training interventions, for example balance training alone or balance training and strength training together, affect the co-activation and the vertical GRF. In order to study the different vertical GRF profiles and co-activation related to it, it is necessary to measure the velocity of old and young subjects while they ascend and descend a set of stairs. Also, the posture of the subjects while ascending and descending the stairs should be recorded in a future study. The different posture between old and young subjects might affect different activation and usage of the muscles and the walking strategy. James & Parker (1989) have noticed old subjects to a use more flexed posture of the trunk while ascending and descending the stairs, and Hortogágyi & De Vita (2000, 1999) reported that old subjects use a more erect position of the lower limbs for a safer movements strategy while descending.

6.5 Conclusion

The present study results provide evidence for the hypothesis that old subjects use a different neuromuscular strategy when ascending and descending stairs compared to young subjects. The correlations and covariate analysis showed that the subjects´ step cycle duration, which is related to the velocity, had a notable effect on the force parameters and the shape of the GRF curve. Thelen et al. (2000) explained that the different muscle activation during the movement is associated with a compensation for age-difference in muscular capabilities, and larger muscle activations may be needed by old subjects to achieve the same mechanical effects as in young subjects.

A future study must be made with larger subject groups to verify the results of this study. The training intervention studies of the co-activation during stepping add to the knowledge of muscle activity in the elderly and their capacity to perform daily living tasks such as ascent and descent of stairs. An intervention study could find solutions for old people to continue their independent living and keep their capacity for ascending and descending the stairs. It also can find a way to decrease falls in the elderly while stair walking.

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Vertical GRF values normalized to body mass while ascent the stairs at maximum velocity (AMV), at self selected velocity (ASV) and descent the stairs at self selected velocity (DSV) in old and young sunbjects. The measured GRF parameters were: #1 Mean values of the entire stance phase (% BW), #9 The first Fz peak, GRF (% BW), #10 Mid-phase minimum point, GRF (% BW), #11 The second Fz peak, GRF (% BW), #12 Mid stance phase, GRF (% BW), #13 Loading phase, GRF (% BW), #14 Unloading phase, GRF (% BW), #15 Loading slope, ΔGRF/Δtime (NS^{-1} % BW^{-1}), #16 Unloading slope, ΔGRF/Δtime (NS^{-1} % BW^{-1}).

	AMV					ASV					DSV				
	Old		Young			Old		Young			Old		Young		
	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value
#1	83,7	9,0	107,2	4,3	<0,001	76,1	5,5	79,5	3,0	0,089	81,6	3,3	78,4	3,5	0,024
#9	131,8	26,8	191,5	16,2	<0,001	103,5	8,4	116,7	7,6	<0,001	147,9	24,3	158,3	13,6	0,220
#10	128,8	30,9	191,2	16,9	<0,001	80,5	6,1	69,6	7,3	<0,001	109,3	36,8	91,1	43,2	0,244
#11	134,8	23,1	191,8	15,6	<0,001	112,4	10,5	116,5	12,8	0,369	118,1	31,0	108,6	32,9	0,450
#12	131,2	27,7	191,5	16,3	<0,001	93,3	2,6	91,7	2,8	0,129	119,4	29,6	109,5	32,4	0,414
#13	83,3	16,5	108,6	10,1	<0,001	63,1	7,8	68,9	8,7	0,076	63,3	14,2	74,7	12,9	0,045
#14	75,8	11,4	103,4	8,5	<0,001	65,4	5,1	63,5	6,0	0,377	69,6	14,5	52,9	15,9	0,008
#15	685,5	277,7	2079,7	430,3	<0,001	528,4	201,6	865,4	291,1	0,001	1053,0	383,3	1144,1	200,3	0,491
#16	-972,4	273,1	-2153,6	289,2	<0,001	-821,2	238,8	-1123,6	186,3	0,002	-558,4	238,9	-716,8	161,7	0,045

APPENDIX 1

APPENDIX 2

Time analysis from AMV in old and young subjects, #5 Step cycle duration, #6 Step frequency, #7 The fractional part of stance phase duration relation to step cycle duration (%), #11 Time for foot touch-down, #12 Time for foot take-off, #12-#11 Complete stance phase duration.

		# 5	# 6	# 7	# 11	# 12	#12 - #11
OLD (n19)	Mean	850,1	1,3	60,1	4894,1	5406,0	512,0
	Sd	250,1	0,3	7,1	243,1	330,4	160,8
YOUNG (n10)	Mean	476,4	2,1	47,8	5041,1	5268,5	227,4
	Sd	51,74	0,3	2,3	282,1	284,4	24,1
	p-value	<0,001	<0,001	<0,001	0,154	0,276	<0,001

Time analysis from ASV in old and young subjects (See description of the parameters above)

		# 5	# 6	# 7	# 11	# 12	#12 - #11
OLD (n19)	Mean	1254,3	0,8	68,0	4909,7	5762,5	852,8
	Sd	250,1	0,2	5,2	289,5	396,8	189,3
YOUNG (n10)	Mean	1007,3	1,0	65,5	4925,2	5583,4	658,2
	Sd	122,1	0,1	2,3	24,0	73,6	69,6
	p-value	0,001	0,004	0,082	0,868	0,172	<0,001

Time analysis from DSV in old and young subjects (See description of the parameters above)

		# 5	# 6	# 7	# 11	# 12	#12 - #11
OLD (n19)	Mean	1206,6	0,9	65,0	4991,7	5782,2	783,0
	Sd	536,5	0,3	3,7	143,3	453,7	384,0
YOUNG (n10)	Mean	878,9	1,2	65,5	4918,7	5497,8	579,1
	Sd	158,7	0,2	3,3	48,5	100,2	122,0
	p-value	0,072	0,019	0,718	0,132	0,063	0,116

Muscular antagonist co-activation (%) from thigh and calf muscle groups during AMV, ASV and DSV in old and young subjects. See description of the GRF parameters in Appendix 1.

VL+VM+RF vs BFcl+ST

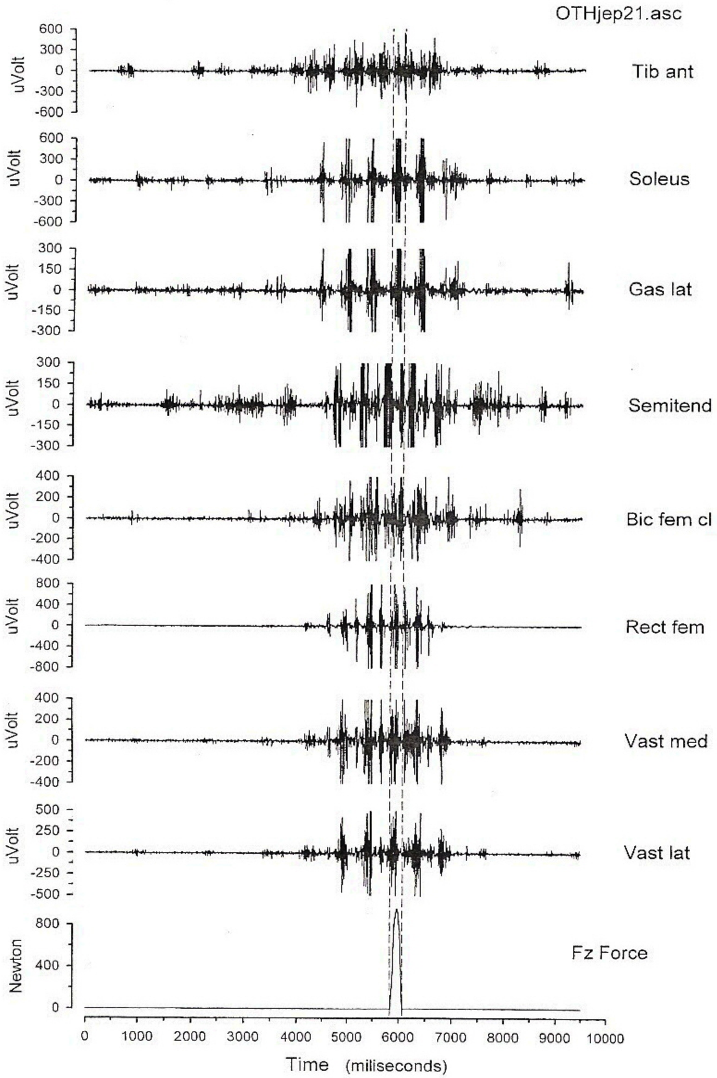
	AMV					ASV					DSV				
	Old		Young			Old		Young			Old		Young		
	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value
#1	47,3	8,5	38,3	7,9	0,010	49,8	10,4	39,1	10,3	0,013	50,9	11,5	39,8	15,1	0,034
#9	53,6	22,3	53,2	23,4	0,960	69,3	22,8	60,5	22,8	0,332	50,2	27,5	29,2	17,9	0,039
#10	50,9	21,4	53,6	23,4	0,763	53,2	20,6	39,2	25,8	0,124	51,3	28,5	39,3	28,4	0,291
#11	52,5	23,8	50,4	25,3	0,827	59,4	21,7	42,7	25,5	0,074	46,3	25,4	41,1	17,2	0,572
#12	52,8	21,8	51,8	23,9	0,918	58,2	12,8	43,1	16,8	0,011	48,2	24,4	36,6	20,7	0,214
#13	51,6	13,6	41,7	12,3	0,065	50,9	16,8	43,2	16,1	0,246	57,2	17,1	34,4	15,5	0,002
#14	40,6	9,3	34,9	15,6	0,234	39,3	14,2	32,4	19,1	0,282	52,1	12,7	49,9	18,9	0,716
#15	53,9	15,7	40,2	12,8	0,024	47,9	18,1	38,5	15,9	0,175	60,1	16,9	35,9	15,6	0,001
#16	35,4	15,5	31,2	15,4	0,488	35,8	14,0	32,7	19,5	0,626	59,6	15,8	49,5	23,6	0,179

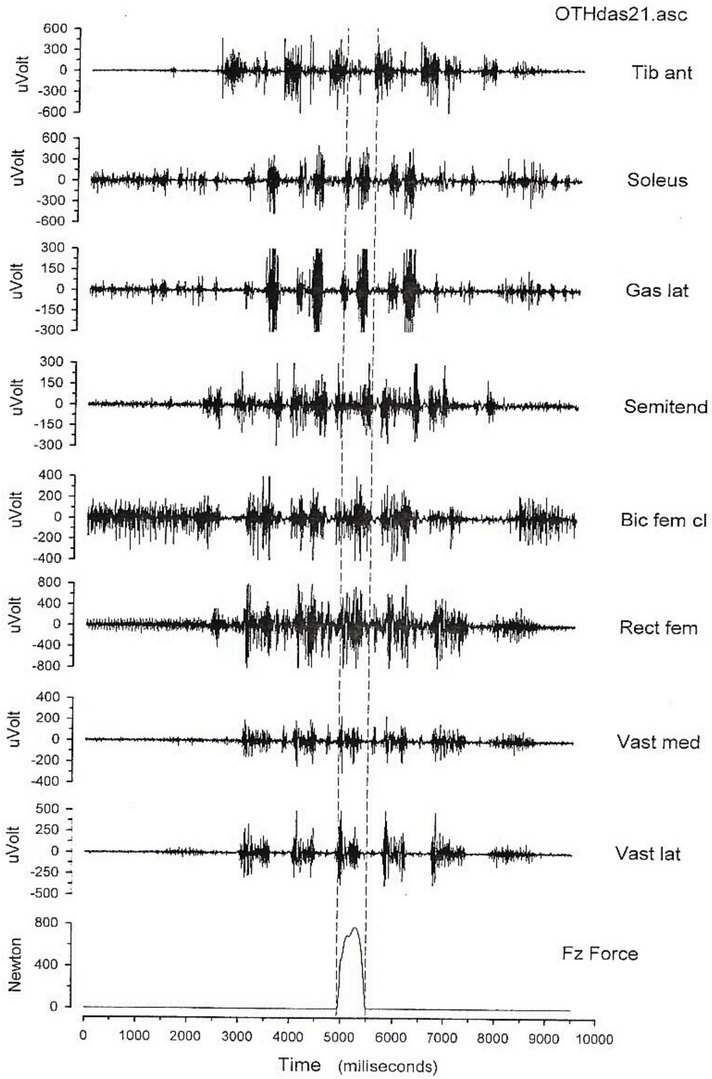
Sol+GasLat vs TA

	AMV					ASV					DSV				
	Old		Young			Old		Young			Old		Young		
	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value
#1	30,7	12,2	28,8	5,3	0,638	31,6	8,0	29.1	5.5	0,384	37,2	9,6	37,2	6,1	0,998
#9	30,3	25,3	25,2	9,3	0,448	45,3	23,3	27.9	15.7	0,026	39,7	21,9	30,7	16,7	0,264
#10	28,6	24,9	24,9	8,8	0,571	45,6	23,7	39.2	24.3	0,498	28,0	17,6	38,4	16,4	0,134
#11	21,9	17,2	24,6	8,3	0,647	18,9	13,4	23.6	10.8	0,354	29,9	15,2	47,9	22,5	0,040
#12	24,8	16,5	24,7	8,4	0,984	28,8	10,0	26.5	7.1	0,526	31,5	12,3	34,8	7,1	0,366
#13	36,1	15,5	29,9	8,9	0,248	42,3	15,9	33.8	10.7	0,142	51,2	17,5	45,9	10,9	0,406
#14	25,9	12,9	28,9	7,1	0,503	24,8	8,8	35.1	4.5	0,000	32,3	11,4	33,6	14,5	0,798
#15	41,9	19,2	33,0	10,8	0,120	40,7	14,5	35.5	13.4	0,352	53,7	17,7	50,2	12,1	0,580
#16	32,4	13,4	40,1	15,9	0,179	38,7	17,6	43.8	8.6	0,399	34,6	15,5	33,1	17,2	0,811

APPENDIX 4

Absolute EMG activation and vertical GRF curve from ascent at maximum velocity in young, the first (jep,) and old, the second (das) subject.





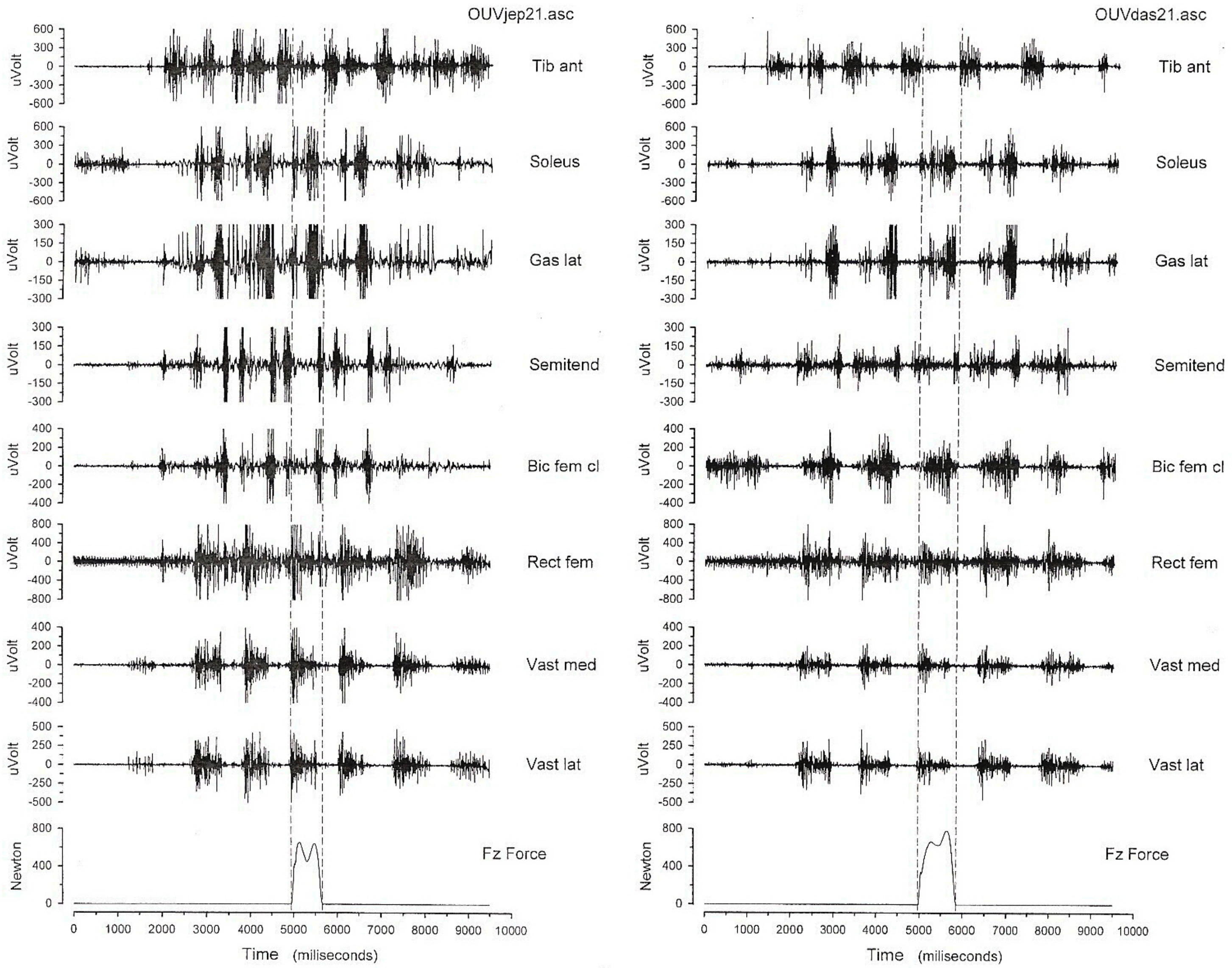
EMG normalized to MVC muscle activation (% of MVC) from eight leg muscles during AMV in old and young subjects. See description of the parameters in Appendix 1.

	#1					#9					#10				
	Old		Young			Old		Young			Old		Young		
	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value
VL	51,9	11,7	43,9	12,4	0,093	59,4	17,3	41,7	27,1	0,041	63,1	18,6	40,1	25,7	0,010
VM	51,2	13,7	45,9	45,9	0,325	63,6	26,7	50,0	23,1	0,184	69,8	26,2	49,9	23,0	0,052
RF	77,7	37,8	81,6	42,8	0,805	95,8	78,2	81,7	63,1	0,627	103,4	75,2	80,7	63,4	0,423
BFcl	51,3	22,9	45,7	15,3	0,496	52,3	33,2	43,1	18,8	0,345	51,9	30,4	42,4	18,9	0,308
ST	43,2	21,7	46,5	33,7	0,753	25,9	15,9	39,3	50,5	0,292	26,6	16,4	39,3	50,5	0,318
GasL	59,1	27,2	84,7	28,1	0,024	96,7	71,8	150,2	62,3	0,057	101,8	68,0	149,5	63,2	0,077
Sol	51,4	23,0	73,8	22,7	0,019	76,9	44,3	127,4	51,9	0,010	80,6	41,1	125,5	51,5	0,016
TA	26,9	10,1	32,9	11,6	0,156	24,2	17,9	32,6	9,7	0,178	21,1	12,3	31,8	8,6	0,021

	#11					#12					#13				
	Old		Young			Old		Young			Old		Young		
	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value
VL	61,4	16,1	61,4	16,1	0,006	58,2	16,1	26,4	18,2	<0,001	73,9	18,3	76,0	19,6	0,779
VM	70,1	25,7	49,9	23,1	0,048	63,9	24,6	37,4	20,2	0,007	69,5	16,3	74,3	19,5	0,483
RF	106,2	73,9	78,7	64,4	0,330	94,7	61,9	65,3	49,6	0,207	99,4	44,9	114,2	50,4	0,425
BFcl	54,7	32,2	39,8	21,3	0,199	53,4	29,5	42,2	20,9	0,295	47,5	23,2	46,2	16,3	0,876
ST	27,2	17,9	37,9	51,2	0,412	25,7	14,9	41,3	53,2	0,383	38,8	22,8	33,4	25,5	0,566
GasL	120,8	51,4	148,3	64,9	0,222	111,5	67,3	147,5	69,3	0,186	53,4	35,1	108,4	25,6	<0,001
Sol	97,3	28,1	118,8	55,4	0,174	83,9	35,7	104,9	46,6	0,185	51,9	26,8	114,1	28,5	<0,001
TA	21,2	12,8	30,1	8,8	0,060	22,4	11,4	25,9	6,1	0,284	27,8	13,1	32,8	10,6	0,308

	#14					#15					#16				
	Old		Young			Old		Young			Old		Young		
	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value
VL	19,3	8,7	11,1	6,3	0,014	76,9	26,1	86,6	22,8	0,332	10,8	7,5	9,9	6,6	0,760
VM	21,8	8,9	15,0	7,2	0,046	68,5	21,2	79,9	20,3	0,175	12,6	4,9	12,1	5,7	0,794
RF	45,5	28,6	46,1	52,9	0,973	93,9	38,0	123,2	44,9	0,075	39,1	27,4	43,9	61,3	0,771
BFcl	55,5	24,8	46,9	18,7	0,344	44,7	19,7	46,5	15,2	0,187	58,6	28,1	46,7	17,9	0,230
ST	50,8	23,6	60,7	40,4	0,410	42,3	26,2	30,2	17,6	0,203	62,1	29,5	66,1	37,1	0,750
GasL	64,1	22,1	59,7	34,2	0,718	40,6	30,9	90,1	19,7	<0,001	36,4	15,9	30,8	18,0	0,395
Sol	46,6	25,3	30,6	16,6	0,083	46,6	29,3	105,3	22,8	<0,001	26,7	23,8	16,2	8,7	0,195
TA	26,6	10,0	34,1	15,6	0,130	29,7	14,4	31,9	11,1	0,667	30,6	12,1	42,1	21,3	0,074

Absolute EMG activation and vertical GRF curve from ascent at self selected velocity in young, the first (jep), and old, the second (das) subject.



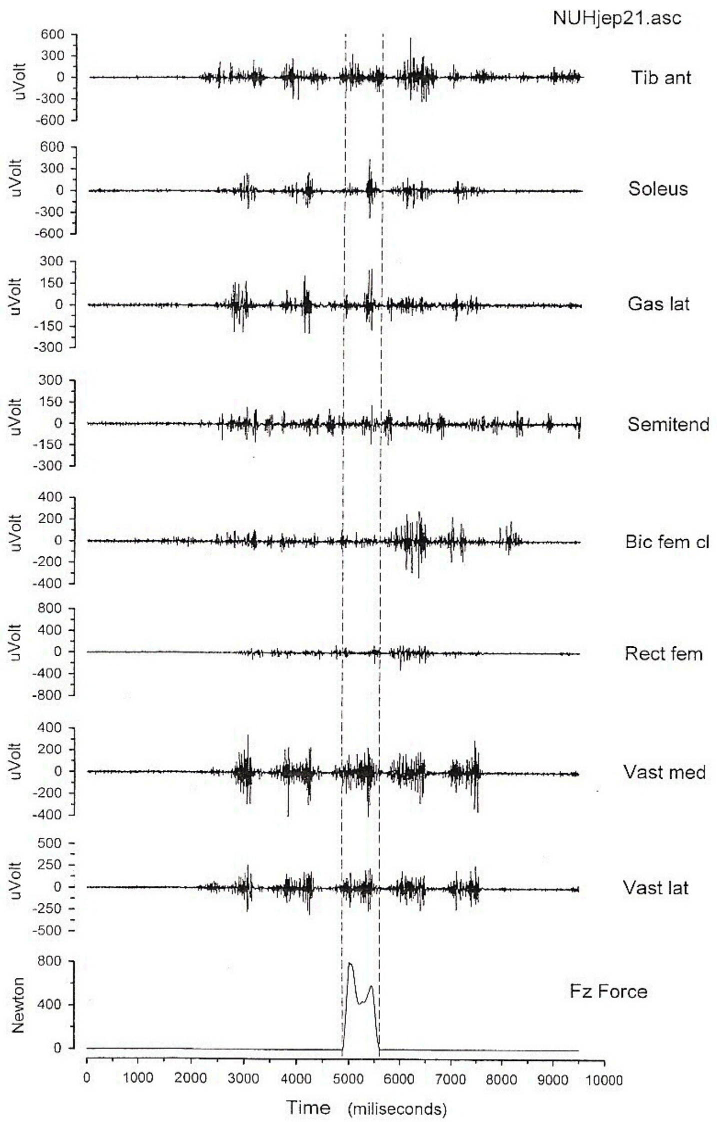
EMG normalized to MVC muscle activation (% of MVC) from eight leg muscles during ASV in old and young subjects. See description of the parameters in Appendix 1.

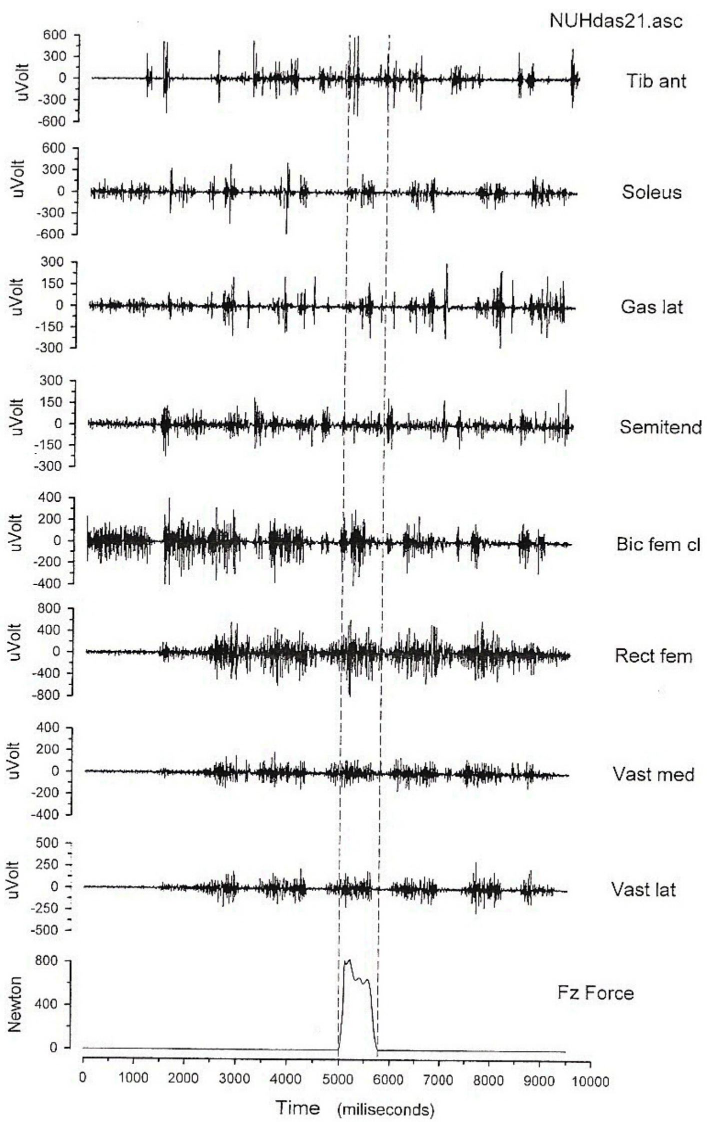
	#1					#9					#10				
	Old		Young			Old		Young			Old		Young		
	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value
VL	38,8	10,7	23,8	15,8	0,005	42,9	14,3	19,3	7,6	<0,001	29,3	15,4	21,2	25,6	0,295
VM	36,8	8,9	16,9	5,4	<0,001	39,5	15,5	15,9	5,8	<0,001	27,7	11,0	14,4	10,2	0,004
RF	43,7	13,3	19,2	7,6	<0,001	38,4	13,7	12,5	7,0	<0,001	29,6	14,4	19,1	9,4	0,026
BFcl	35,6	13,4	13,2	3,4	<0,001	37,5	19,8	18,1	11,2	0,008	26,2	21,7	6,9	4,1	0,001
ST	25,8	9,6	13,1	5,9	0,001	23,6	13,8	8,1	3,6	<0,001	10,4	5,3	4,2	2,6	0,002
GasL	41,3	16,3	39,1	12,5	0,711	25,4	26,0	19,6	12,1	0,516	29,9	25,8	24,8	15,6	0,574
Sol	39,1	12,5	34,7	9,8	0,344	28,9	17,0	28,1	18,8	0,905	34,4	20,5	27,4	12,6	0,335
TA	22,5	11,1	13,4	5,5	0,024	29,6	21,8	14,9	20,4	0,091	20,4	20,8	9,1	5,4	0,105

	#11					#12					#13				
	Old		Young			Old		Young			Old		Young		
	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value
VL	31,2	17,8	16,9	29,7	0,115	34,2	11,9	18,4	13,3	0,003	63,5	20,3	39,2	9,9	<0,001
VM	32,3	18,1	6,0	4,8	<0,001	32,9	8,9	13,2	5,4	<0,001	58,7	17,3	31,8	7,3	<0,001
RF	33,2	19,9	14,9	15,6	0,018	33,6	11,8	16,0	7,3	<0,001	67,7	22,7	28,9	9,4	<0,001
BFcl	38,0	28,1	12,7	9,4	0,002	32,1	20,1	10,4	3,4	<0,001	34,9	14,2	16,9	6,9	0,001
ST	19,0	14,4	15,3	13,5	0,506	15,6	8,8	6,5	4,3	0,005	31,6	11,7	13,3	7,7	<0,001
GasL	109,1	52,3	95,6	39,8	0,483	44,3	20,4	48,1	13,8	0,608	27,2	19,3	29,6	10,9	0,725
Sol	79,5	38,6	54,3	18,3	0,063	45,1	18,3	42,4	13,0	0,683	33,3	15,6	37,9	17,0	0,461
TA	21,0	19,7	18,2	9,8	0,676	21,3	18,1	13,9	7,3	0,230	27,9	13,9	13,4	7,0	0,005

	#14					#15					#16				
	Old		Young			Old		Young			Old		Young		
	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value
VL	12,5	7,9	18,7	41,9	0,655	68,4	24,3	48,7	13,2	0,025	9,4	6,5	19,0	42,3	0,334
VM	12,3	6,6	6,4	4,9	0,019	64,9	20,1	39,5	9,4	<0,001	10,0	5,7	6,2	4,3	0,073
RF	27,4	13,1	14,4	13,7	0,018	78,4	29,9	36,7	14,9	<0,001	29,4	16,0	14,5	12,7	0,017
BFcl	46,5	24,6	15,6	4,6	<0,001	34,3	14,9	15,7	5,7	<0,001	48,0	25,5	16,6	4,4	<0,001
ST	36,9	20,3	29,5	14,3	0,308	33,5	12,2	14,7	9,4	<0,001	43,6	22,5	32,4	17,3	0,181
GasL	52,7	27,7	28,9	21,6	0,026	25,6	16,5	33,2	12,7	0,214	33,2	26,8	17,5	21,4	0,121
Sol	33,0	16,0	11,3	8,3	0,000	32,9	19,3	43,9	22,1	0,174	16,7	14,6	4,7	1,1	0,002
TA	19,2	11,3	11,9	3,6	0,061	27,1	13,6	13,5	5,7	0,001	21,4	9,7	13,2	6,2	0,022

Absolute EMG activation and vertical GRF curve from DSV in young, the first (jep), and old, the second (das) subject.





APPENDIX 8

EMG normalized to MVC muscle activation (% of MVC) from eight leg muscles during DSV in old and young subjects. See description of the parameters in Appendix 1.

	#1					#9					#10				
	Old		Young			Old		Young			Old		Young		
	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value
VL	33,5	6,6	23,0	17,3	0,026	43,6	13,4	31,8	24,4	0,101	43,6	17,1	25,3	19,9	0,015
VM	35,8	9,1	19,3	8,0	<0,001	48,8	23,5	24,4	10,9	0,001	45,7	19,9	19,3	10,7	<0,001
RF	43,7	13,0	25,3	11,5	0,001	54,4	24,1	32,0	18,3	0,016	51,4	21,2	24,9	14,4	0,002
BFcl	28,7	11,9	10,5	6,7	<0,001	28,5	17,9	9,2	5,1	<0,001	25,2	16,6	8,9	7,4	0,007
ST	19,9	8,9	8,7	6,1	0,002	15,8	9,9	5,7	3,5	0,005	18,3	14,0	6,9	4,8	0,020
GasL	25,1	13,4	19,3	11,7	0,261	18,4	13,5	20,0	17,3	0,780	29,4	29,6	23,6	19,7	0,587
Sol	23,1	7,3	15,8	7,1	0,015	19,6	9,1	13,9	16,4	0,234	25,5	20,9	22,8	16,1	0,716
TA	26,9	11,1	17,2	7,3	0,020	42,3	18,9	24,8	15,7	0,019	25,5	21,6	14,4	10,7	0,079

	#11					#12					#13				
	Old		Young			Old		Young			Old		Young		
	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value
VL	43,9	11,9	22,9	9,6	<0,001	40,4	12,0	25,4	17,2	0,010	38,1	9,4	24,2	7,9	<0,001
VM	46,9	19,2	22,4	14,4	0,002	45,2	19,7	21,2	11,0	0,001	40,3	15,6	22,5	8,6	0,001
RF	53,6	16,4	22,6	9,3	<0,001	48,9	15,7	25,8	14,4	0,001	43,6	16,3	29,7	16,3	0,040
BFcl	24,5	16,6	9,8	8,7	0,015	25,6	17,6	9,7	7,5	0,002	38,8	21,2	10,1	2,9	<0,001
ST	18,9	12,7	8,1	4,8	0,016	16,6	10,2	7,1	3,4	0,008	19,8	9,7	7,4	6,4	0,001
GasL	27,9	22,8	24,7	21,6	0,713	22,9	15,8	22,7	17,3	0,974	23,1	14,5	19,5	8,8	0,408
Sol	28,6	16,9	24,8	16,5	0,569	22,3	11,0	21,4	16,1	0,854	23,2	9,3	15,4	8,6	0,036
TA	23,9	21,7	16,4	10,2	0,217	30,9	17,5	17,2	10,5	0,014	32,3	12,4	17,7	7,9	0,002

	#14					#15					#16				
	Old		Young			Old		Young			Old		Young		
	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value	Mean	Sd	Mean	Sd	p-value
VL	26,3	9,7	18,3	26,9	0,257	36,9	9,8	22,8	5,9	<0,001	17,8	9,8	18,9	35,5	0,899
VM	30,7	11,3	15,2	7,8	0,001	38,7	14,7	22,3	8,9	0,003	22,7	10,6	15,1	8,3	0,610
RF	43,3	17,4	24,4	13,1	0,005	41,5	15,3	29,2	16,2	0,054	40,5	16,9	25,5	18,3	0,035
BFcl	27,0	12,9	12,6	11,2	0,006	40,5	22,7	10,2	2,9	<0,001	26,2	10,1	13,1	12,1	0,004
ST	21,5	9,3	10,7	5,7	0,002	20,7	10,4	7,8	7,4	0,002	22,0	9,6	10,9	6,4	0,003
GasL	28,3	17,9	15,5	13,8	0,060	24,1	15,0	19,7	8,4	0,323	23,4	14,4	13,7	14,4	0,098
Sol	22,2	8,5	11,4	8,9	0,003	23,7	9,9	16,1	8,8	0,530	15,2	5,5	7,8	5,9	0,002
TA	27,3	14,3	21,7	13,7	0,319	30,9	11,2	16,3	6,8	0,001	31,8	16,5	22,7	14,6	0,153

APPENDIX 10

The correlations from GRF parameters and time parameters of step cycle during AMV in old and young subjects. See description of the GRF parameters in Appendix 1. The time parameters of step cycle were: #5 Step cycle duration, #12-#11 Complete stance phase.

	Old		Young	
	#5	#12-#11	#5	#12-#11
#1	-.814***	-.863***	.154	.030
#9	-.832***	-.895***	.161	.092
#10	-.882***	-.924***	.174	.106
#11	-.855***	-.920***	.146	.078
#12	-.875***	-.923***	.163	.094
#13	-.852***	-.893***	.330	.325
#14	-.873***	-.837***	.160	-.025
#15	-.561*	-.743***	-.852**	-.856**
#16	.726***	-.762***	.305	.545

* p < 0.05, ** p < 0.01, *** p < 0.001

The correlations from GRF parameters and time parameters of step cycle during ASV in old and young subjects. See description of the GRF parameters in Appendix 1 and time parameters of step cycle above.

	Old		Young	
	#5	#12-#11	#5	#12-#11
#1	-.868***	-.860***	-.491	-.598
#9	-.535*	-.436	-.550	-.556
#10	.382	.503*	.301	.308
#11	-.248	-.303	-.108	-.215
#12	-.272	-.084	.011	.030
#13	-.742***	-.688***	-.596	-.730*
#14	.089	.055	.037	.085
#15	-.874***	-.877***	-.566	-.727*
#16	.825***	.889***	.605	.605

* p < 0.05, *** p < 0.001

The correlations from GRF parameters and time parameters of step cycle during DSV in old and young subjects. See description of the GRF parameters in Appendix 1 and time parameters of step cycle above.

	Old		Young	
	#5	#12-#11	#5	#12-#11
#1	.121	-.091	.632	-.669*
#9	.615**	-.639**	-.620	.652*
#10	.163	-.214	.613	-.608
#11	.222	-.266	.675*	-.661*
#12	.281	-.329	.656*	-.645*
#13	-.160	.192	.511	-.553
#14	-.051	.004	.763**	-.759**
#15	.729***	-.747***	.267	-.306
#16	-.389	.341	-.400	.388

* p < 0.05, ** p < 0.01, *** p < 0.001

APPENDIX 11

Analyse of covariance for GRF parameters between old and young women with step cycle duration as a covariate during AMV. The GRF parameters were: #1 the entire stance phase, #9 the first peak, #10 the mid-phase minimum point, #11 the second peak, #15 loading slope, #16 unloading slope.

	F	p-value
#1	34,6	<0.001
#9	32,9	0.003
#10	48,1	0.013
#11	34,3	0.001
#15	7,2	<0.001
#16	14,7	<0.001

Analyse of covariance for GRF parameters between old and young women with step cycle duration as a covariate during ASV. See description of the GRF parameters above.

	F	p-value
#1	54,7	<0.001
#9	9,8	0.004
#10	3,4	0.078
#11	1,3	0.266
#15	26,4	<0.001
#16	39,9	<0.001

Analyse of covariance for GRF parameters between old and young women with step cycle duration as a covariate during DSV. See description of the GRF parameters above.

	F	p-value
#1	0,8	0,380
#9	15,1	0.001
#10	1,1	0.301
#11	1,8	0.188
#15	23,4	0,000
#16	4,3	0,047