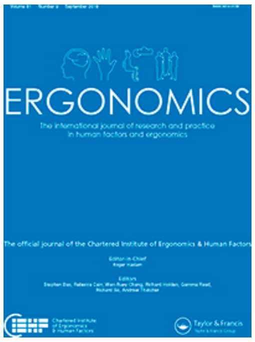

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The influence of age on isometric endurance and fatigue is muscle dependent: a study of shoulder abduction and torso extension

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The present study examined differences in isometric muscle capacity between older (55–65 years) and younger (18–25 years) individuals. A total of 24 younger and 24 older participants (gender balanced within each group) performed sustained shoulder abductions and torso extensions to exhaustion at 30%, 50% and 70% of individual maximal voluntary contraction (MVC). Along with endurance time, manifestations of localized fatigue were determined based on changes in surface electromyographic signals obtained from the shoulder (middle deltoid) and the torso (multifidus and longissimus thoracis) muscles. Strength recovery was monitored using post-fatigue MVCs over a 15-min period. Compared to the younger group, older individuals exhibited lower muscular strength, longer endurance time and slower development of local fatigue. Age effects on fatigue were typically moderated by effort level, while effects of gender appeared to be marginal. Non-linear relationships between target joint torque and endurance time were observed, with effects of age differing between shoulder abduction and torso extension. Overall, the effects of age on endurance and fatigue were more substantial and more consistent for the shoulder muscle than for the torso muscles and were likely related to differences in muscle fibre type composition. For strength recovery rates, no significant age or gender effects were found in either experiment. In summary, this study suggests that differences in isometric work capacity do exist between older and younger individuals, but that this effect is influenced by effort level and the muscle tested.

Keywords: Aging; Isometric exercise; Muscle fatigue; Muscle endurance; Strength recovery

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1. Introduction

Census Bureau population projections suggest that there will be around 75 million people over the age of 55 years in the United States in 2010, resulting in an increase of about 46% in the number of older workers between the ages of 55 to 64 years compared to the year 2000 (Horrigan 2004). The increasing percentage of older workers in the workplace necessitates re-evaluation of their physical work capacity. A decline in physical capability may exist in general among older workers, but limited data are available.

Aging has well-known associations with sarcopenia (loss of skeletal muscle mass). Although age-related decreases in physical activity may contribute to this loss, several underlying changes in the neuromusculoskeletal system have been identified as primary contributors to sarcopenia, including a reduction in the number of active motor units, a slower firing rate of motor units, a smaller number of muscle fibres and smaller fibre size (Campbell *et al.* 1973, Lexell *et al.* 1988, Evans 1995). As a result, age-related declines in muscular strength have generally been reported, but these losses appear to vary among different muscle groups (Bemben *et al.* 1991, Bäckman *et al.* 1995).

Along with sarcopenia, a shift in the relative proportions of muscle fibre types occurs with advancing age due to a selective reduction in type II (fast-twitch) fibres (Lexell 1995, Klein *et al.* 2003). The shift in fibre type proportion has been hypothesized to play at least a partial role in the longer endurance times reported for older individuals in sustained knee extension and elbow flexion (Larsson and Karlsson 1978, Bilodeau *et al.* 2001b). In addition to endurance, aging also results in a higher fatigue resistance, based on changes in electromyographic (EMG) measures. At the same levels of prolonged submaximal efforts, older individuals have demonstrated lower rates of EMG amplitude changes during exercises involving the elbow flexors (Bilodeau *et al.* 2001b) and slower rates of decline in EMG spectral measures recorded from the ankle dorsiflexors (Merletti *et al.* 1992, Yamada *et al.* 2000). Further study is necessary to investigate whether age effects consistently exist across muscle groups, specifically for muscles frequently used in occupational settings.

In addition to muscle strength and fatigue, physical work capacity is influenced by post-exertion recovery (e.g. in intermittent or cyclic work). However, the relationship between aging and recovery from exercise-induced local fatigue has received relatively little attention (Allman and Rice 2001). Several measures (e.g. measurements of voluntary strength, EMG changes, twitch response) have been used to monitor recovery, but evidence is often contradictory. For example, older subjects were found to have slower recovery of muscle fibre conduction velocity and EMG median frequency (Hara *et al.* 1998), yet no significant age effects on recovery of voluntary strength and EMG parameters were reported (Allman and Rice 2001, Bilodeau *et al.* 2001a).

The purpose of the present study was to quantify differences in muscular endurance, fatigue and recovery between older and younger individuals in response to several levels of sustained isometric effort. Existing evidence has clearly identified several changes in the neuromuscular system and demonstrated some consistent age effects on muscular performance and recovery. However, most of this evidence has been obtained from a limited set of muscles (Allman and Rice 2002). In this study, two muscle functions were investigated; specifically, shoulder abduction (middle deltoid) and torso extension (lumbar extensors). These were selected for three main reasons. Occupationally, symptoms and complaints related to the shoulder (Van der Windt *et al.* 2000) and torso

(Guo *et al.* 1999) are common among industrial workers. These muscles differ in fibre composition. While the proportion of slow-twitch fibres of the middle deltoid is about 53–69% (Manta *et al.* 1996), the lumbar extensors (e.g. the longissimus muscle) have approximately 71% slow-twitch fibres (Jørgensen 1997). Furthermore, shoulder and torso muscles can be considered functionally different (task vs. postural muscles, respectively). The last two reasons are related to each other. The functional distinction between the muscles is due to differences in fibre type composition and the lumbar extensors were considered as postural muscles due to the high proportion of slow-twitch fibres. It was therefore hypothesized that age-related differences in muscular capacity would differ between the two muscle groups. Given the projected increase in the older worker population in the workplace, the study was focused on older individuals whose age was typical of that at the end of working life. As has been done in several recent studies, effort levels used here were normalized to individual capacity in order to isolate endurance/fatigue from confounding effects of age-related strength decrements.

2. Methods

Fatigue development and recovery were evaluated under different workload conditions using a repeated measures design. To address variations in motor unit control with exertion level (De Luca *et al.* 1996), three levels of sustained isometric activity were used (30, 50 and 70% of maximum voluntary contraction (MVC)). Two separate experiments were conducted, one addressing shoulder abduction and the other torso extension.

2.1. *Participants*

For each experiment, a total of 24 younger and 24 older individuals were recruited from the local community, with gender balanced within each group (table 1). Only those with moderate levels of (self reported) daily physical activities and having had no injuries or disorders in the past 12 months were included. All older participants were screened for any contraindications to performance in experimental procedures based on examination of an occupational physician. The younger participants typically held non-sedentary jobs. The older individuals, although not all held a full time job, performed regular moderate exercise. Informed consent, using procedures approved by the Virginia Tech Institutional Review Board, was obtained prior to the experiment.

2.2. *Procedures*

Each experiment required three sessions, performed on 3 separate days, with a minimum of 2 d of rest in between. Each session consisted of pre-fatigue MVCs,

Table 1. Descriptive data on participants. Values are mean $\pm$ standard deviations.

	Experiment 1 Shoulder abduction		Experiment 2 Torso extension	
	Younger	Older	Younger	Older
Age (years)	21.7 $\pm$ 1.9	61.5 $\pm$ 4.3	21.5 $\pm$ 1.2	60.8 $\pm$ 4.0
Stature (cm)	170.8 $\pm$ 7.7	167.3 $\pm$ 7.8	172.8 $\pm$ 9.0	166.9 $\pm$ 7.7
Mass (kg)	71.5 $\pm$ 13.6	78.5 $\pm$ 14.0	71.6 $\pm$ 10.9	77.0 $\pm$ 14.1

endurance testing (at an effort level of 30, 50 or 70% MVC) and post-fatigue (recovery) MVCs. To minimize potential order effects, effort levels were performed in a counterbalanced order for each age and gender group. Detailed procedures for each experiment are described below.

2.2.1. Experiment 1: Shoulder abductions. Each participant was comfortably stabilized with shoulder and waist straps in a seated position in a dynamometer (Biodex^{TM} System 3 Pro Medical System, Biodex Medical Systems, Shirley, NY, USA). The dynamometer's centre of rotation was aligned with the centre of the shoulder joint, approximated below the acromial process according to Nussbaum and Zhang (2000). After a brief warm up, each participant was instructed to perform MVCs by maximally abducting their right arm in the frontal plane against the dynamometer padding while the arm was horizontal (figure 1a). The left arm remained resting at the participant's side. Each recorded MVC value was corrected for gravitational effects on the participant's arm and dynamometer attachment. A minimum of three MVCs were performed, with 2 min of rest given between. Additional MVCs were performed if the torque exerted markedly increased (more than 10%) from the previous trial. The largest torque was designated as the participant's MVC.

Following a 10 min rest, each participant performed an isometric endurance test at one of the three effort levels, with procedures as follows. All postures were the same as those used during the MVC tests. After brief practice, each participant was instructed to maintain the exertion level within $\pm 5\%$ of the target torque for as long as possible. Torque feedback was displayed on a computer screen located directly in front of the participant. Following cessation of the isometric endurance test, a series of MVCs was then performed (post-fatigue MVC) during recovery at 0, 1, 2, 5, 10 and 15 min. A similar sequence of pre-fatigue MVCs, endurance test and post-fatigue MVCs was repeated on subsequent days at the remaining effort levels. Non-threatening verbal encouragement was provided throughout each test and efforts were made to ensure that participants were comfortable. All postures and fixture configurations were recorded and kept consistent across experimental days.

2.2.2. Experiment 2: Torso extensions. Torso extension tasks were performed using procedures similar to those in the shoulder exertions (pre-fatigue MVCs, endurance test and post-fatigue MVCs). Each participant was stabilized using a hip fixture designed to maintain an upright posture with hips and knees strapped to padded constraints (figure 1b). A force plate (OR6; Advanced Mechanical Technology Inc., Watertown, MA, USA) was placed underneath the fixture and torques exerted (at the L5/S1 level) were estimated from the recorded force and relative distance to the force plate (Granata *et al.* 1996). During MVCs, participants were instructed to stand upright and to maximally extend the torso in the sagittal plane against padding placed over the upper torso (as shown in figure 1b). A strap over the upper torso was used to maintain an upright posture. All other test procedures were the same as those employed during shoulder abductions.

2.3. *Surface electromyographic signal acquisition and processing*

Surface EMG signals were obtained from the middle deltoid during shoulder abductions, using a pair of Ag/AgCl electrodes (inter-electrode distance of 2.5 cm) located over the muscle belly (Hermens *et al.* 1999). During torso extensions, four pairs of the electrodes

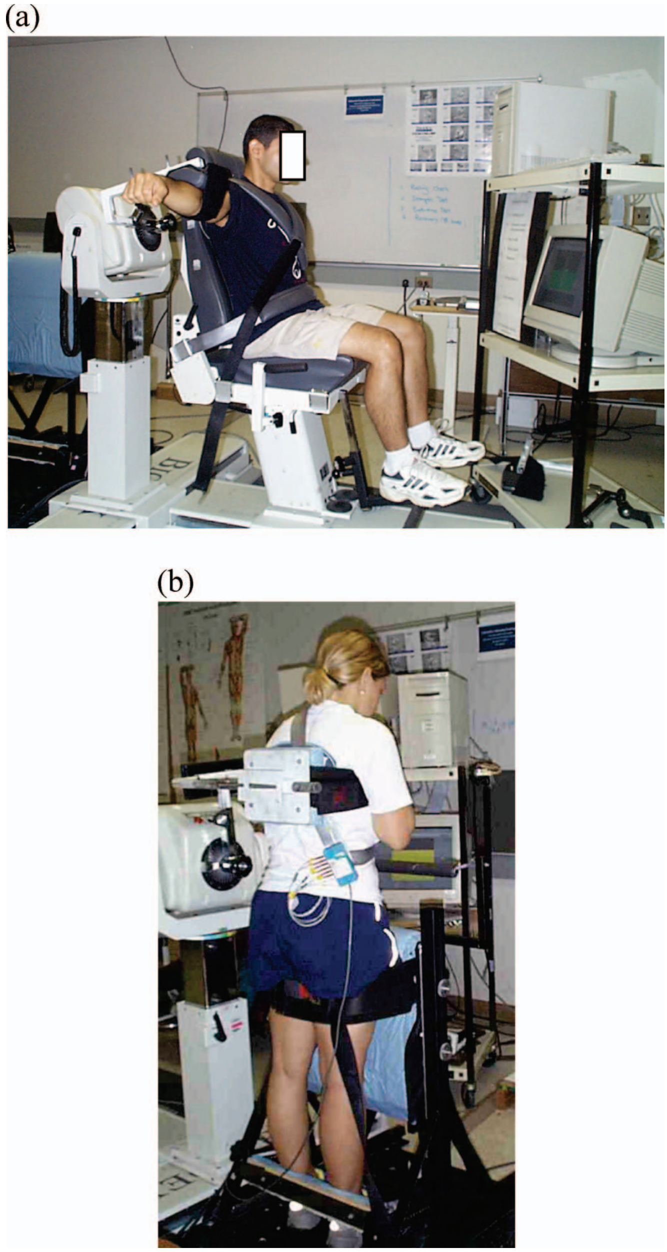


Figure 1. Experimental arrangement for (a) shoulder abduction and (b) torso extension.

were placed bilaterally over the erector spinae muscles at the L1 and L4/L5 levels, to target the longissimus thoracis and the multifidus muscles, respectively, according to Biedermann *et al.* (1990) and Larivière *et al.* (2002). Electrode locations were marked and recorded to ensure consistent placement in subsequent experimental sessions. Prior to electrode placement, the skin was shaved, gently abraded and cleaned with rubbing alcohol, with an inter-electrode resistance less than 10 kΩ considered acceptable. The clavicle or the C7 vertebral process was used for grounding.

EMG signals were recorded continuously during both experiments using an EMG amplifier system (Measurement System Inc., Ann Arbor, MI, USA). Raw signals were pre-amplified ($\times 100$) near the electrode site and hardware filtered at 10–500 Hz. Raw EMG was sampled at 2048 Hz, while EMG root mean square (RMS) was sampled at 128 Hz (110 ms time constant). The former were then divided into 2 s samples and subsequently divided into three 1 s overlapping windows (Luttmann *et al.* 1996). A Hanning window and Fast Fourier transform were applied to each sample window. A final power spectral density was calculated as an average value and used to determine the mean and median frequencies (MnPF and MdPF, respectively) according to Merletti and Lo Conte (1995). EMG RMS was low-pass filtered using software (Butterworth, zero phase-lag, 4th order, 3 Hz cutoff). Each 1-s sample of EMG RMS taken during endurance tests was averaged and normalized (nRMS) against maximum RMS values obtained during initial MVCs.

2.4. *Analysis*

Independent variables included age group, gender and level of submaximal effort, while dependent measures were endurance time, rates of EMG changes (nRMS, MnPF and MdPF), rate of MVC decline and rate of strength recovery. Endurance time was defined as the time during which torque was maintained in the target zone ($\pm 5\%$). Linear regressions were applied to time-dependent changes in EMG measures (RMS, MnPF and MdPF). The slopes obtained were then normalized to intercept values to obtain rates of EMG change in %/min. Rates of MVC decline (%/min) were computed as the percentage reduction in MVC (pre- vs. post-fatigue MVC) relative to individual endurance time. Strength recovery (post-fatigue MVC) was also represented as a percentage of pre-fatigue MVC.

A three-way repeated measures ANOVA was generally used to examine the presence of main and interaction effects of age, gender and effort level. Since individual strength (MVC) may be a factor influencing fatigue development, an initial test was conducted to investigate the effect of this potential covariate. If the covariate (MVC) was significant and a common slope parameter existed, a three-factor repeated measures analysis of covariance (ANCOVA) was chosen. Results showed that the prerequisite ANCOVA conditions were not found for any dependent measures during the shoulder experiment, but were observed for all EMG-based fatigue parameters for the torso. Thus, for the latter measures, ANCOVA was employed following Winer *et al.* (1991). Where relevant, post-hoc analyses were conducted using Tukey's HSD test. To examine the relationship between endurance time and target torque magnitude, logarithmic transformations were applied for the latter data and then regression analysis was performed to determine the existence of age and gender effects on the relationship.

To analyse strength recovery, post-fatigue MVCs were fitted to exponential models, $\mathrm{Y} = \mathrm{A} * (1 - \exp^{-\lambda t})$, as suggested by Elfving *et al.* (2002), where λ represents the rate of recovery (per min). Subsequently, any effects of the independent variables on λ were determined using a three-way repeated measures ANOVA. Repeatability of pre-fatigue MVC across days was also of interest (since different MVCs were obtained on different days) and this was assessed using intra-class correlations (ICC), SEM and coefficients of variation (CV) following Denegar and Ball (1993) and Elfving *et al.* (1999). Significance for statistical tests was concluded at $p < 0.05$, unless otherwise specified.

3. Results

There were effects of effort level for all measures, with some evidence of age and age × effort level interaction effects for most of the measures. More detailed results for each dependent measure are described in table 2 and below.

3.1. *Initial maximum voluntary contraction*

Age and gender significantly affected isometric strength in both experiments (figure 2). Mean shoulder abduction MVCs were 64.5 and 52.4 Nm, respectively, for younger and older participants (a difference of approximately 19%). An interactive age × gender effect was also significant, with a greater age-related difference among males than females. For torso extension, a larger MVC discrepancy between the two age groups (about 27%) was found, with an age × gender interaction trend observed ($p = 0.12$). For both experiments, MVC across days was found to be highly repeatable (ICC > 0.96) with fairly small variability (SEM 2.4 Nm for shoulder abduction and 10.5 Nm for torso extension; CV < 4.9% for both).

3.2. *Endurance time*

Shorter endurance times were associated with increased effort level (figure 3). The effect of age on endurance time was significant for the shoulder (with a difference of 13.2% across effort levels), but not significant for torso extension. Gender was not significant for shoulder endurance, but a trend was observed during torso extensions ($p = 0.11$), with females having 11% longer endurance across effort levels. A trend indicating an age × effort level interaction was obtained for the shoulder ($p = 0.13$), suggesting a greater age-related discrepancy at lower effort levels.

Table 2. Summary of main and two-factor interactive effects for each dependent measure, during shoulder abduction (SA) and torso extension (TE).

		Main effects			Interactions		
Measure	Task	A	G	EL	A × G	A × EL	G × EL
Endurance	SA	*	NS	***	NS	NS	NS
	TE	NS	NS	***	NS	NS	NS
EMG RMS	SA	NS	NS	***	NS	NS	NS
	TE†	NS/NS	NS/NS	***/***	NS/NS	NS/NS	NS/NS
EMG MnPF	SA	***	NS	***	NS	*	NS
	TE†	*/**	NS/NS	***/***	NS/*	***/***	NS/NS
EMG MdPF	SA	***	NS	***	NS	*	NS
	TE†	NS/**	NS/NS	***/***	*/*	***/***	NS/NS
Rate of MVC decline	SA	*	NS	***	*	NS	NS
	TE	NS	NS	***	NS	NS	NS
Recovery rate	SA	NS	NS	NS	NS	NS	NS
	TE	NS	NS	NS	NS	NS	NS

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

†Values for the longissimus thoracis and multifidus muscles, respectively.

A = age; G = gender; EL = effort level; EMG = electromyographic; RMS = root mean square; MnPF = mean power frequency; MdPF = median power frequency; MVC = maximum voluntary contraction.

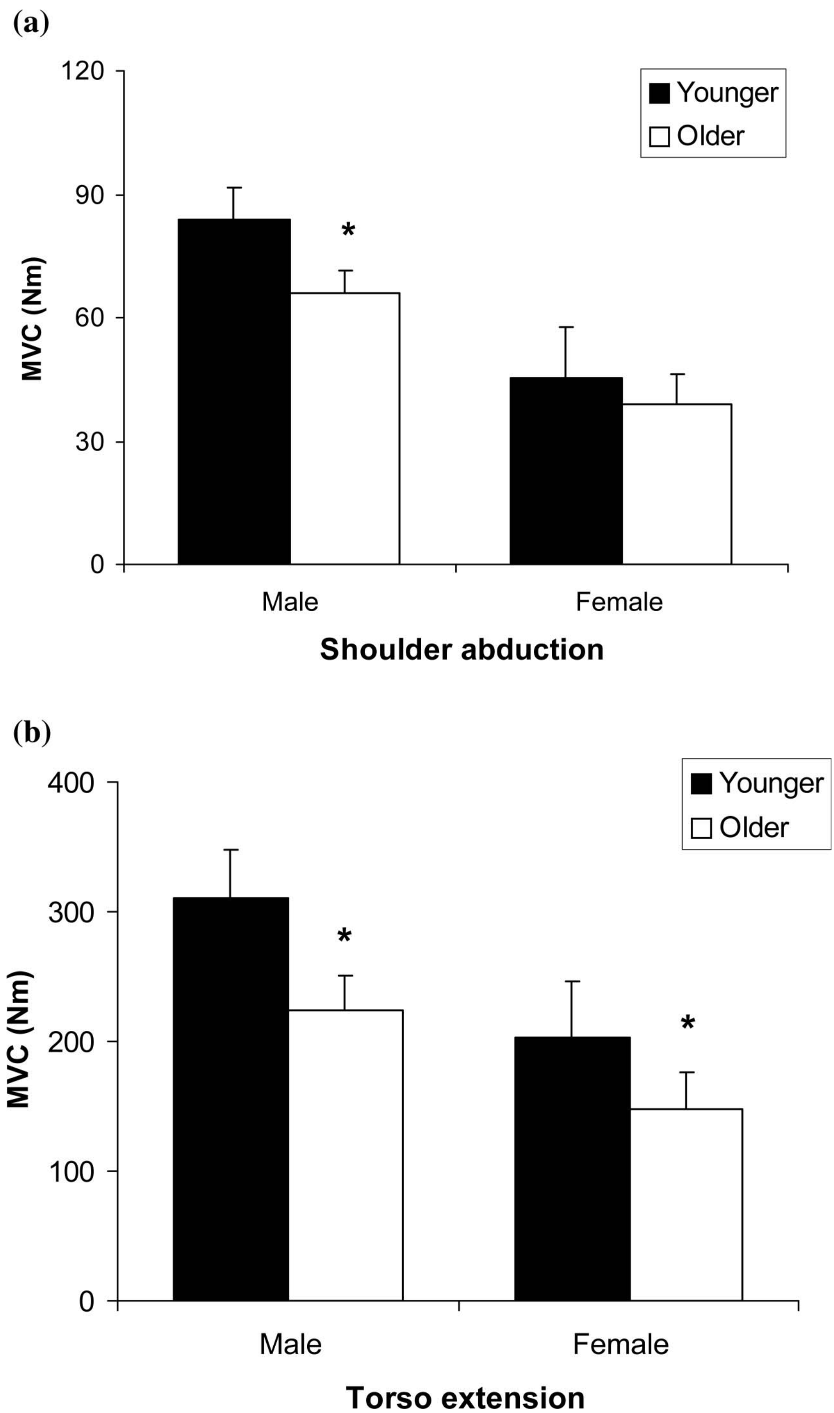


Figure 2. Maximum voluntary contraction (MVC) values for (a) shoulder abduction and (b) torso extension. Error bars represent standard deviations and * indicates significant differences.

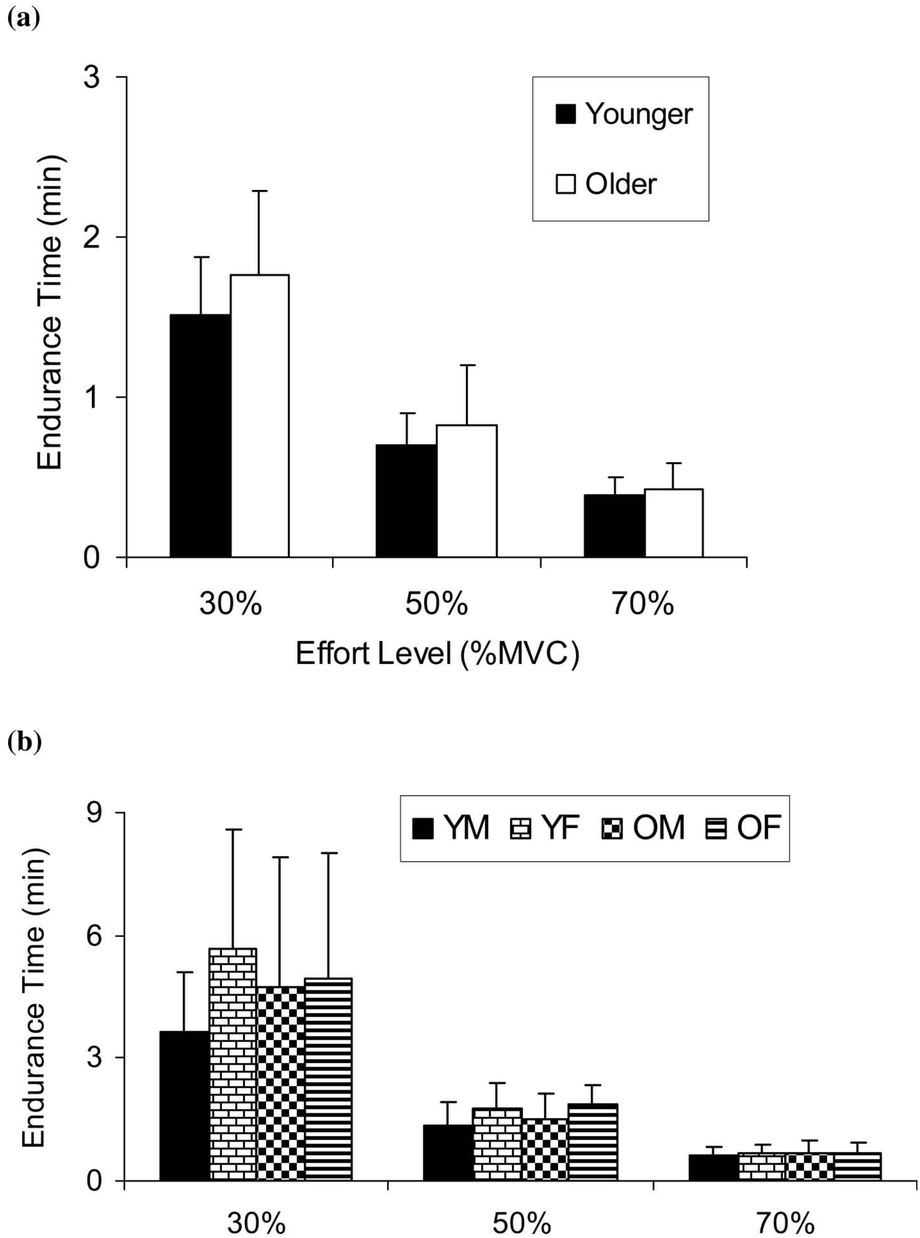
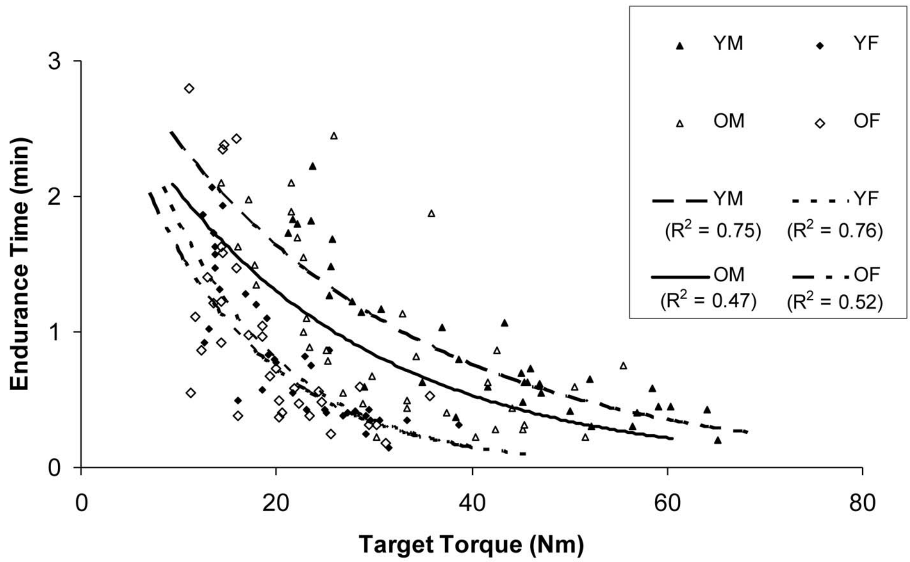


Figure 3. Endurance times for (a) shoulder abduction and (b) torso extension. Error bars represent standard deviations. YM = younger male; YF = younger female; OM = older male; OF = older female; MVC = maximum voluntary contraction.

Endurance time demonstrated an inverse relationship with target torque magnitude (figure 4) and was well-characterized using a negative exponential function ($r^2 = 0.46 - 0.76$). Gender effects were significant for both experiments. For the shoulder, an age effect

(a)



(b)

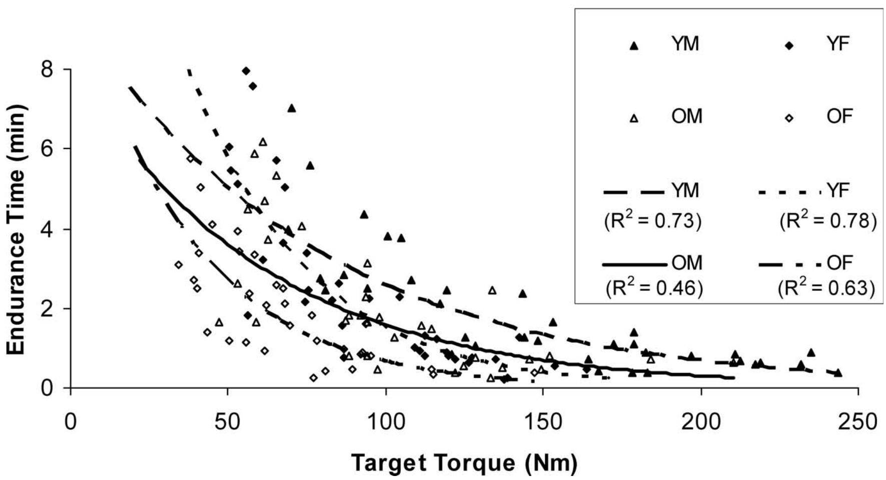


Figure 4. Relationships between endurance time and target torque fitted using exponential curves for (a) shoulder abduction and (b) torso extension. YM = younger male; YF = younger female; OM = older male; OF = older female.

trend was observed ($p = 0.10$) with almost overlapping curves between younger and older females. For the torso, a significant difference between both age groups was found, with a distinct upward shift in the younger group.

3.3. *Rate of maximum voluntary contraction decline*

Both experiments induced substantial reductions in maximum strength, ranging from about 4% per min to 40% per min. These declines were significantly greater at higher effort levels, with rates at 70% MVC three to four times greater than those at 30% MVC. Older participants had lower rates of MVC decline (about 30% for the shoulder and 14% for the torso) across effort levels, but the age effect was significant only for the shoulder (figure 5), not for torso. While a gender effect was not observed at the shoulder, its interaction with age was significant, as demonstrated by the smaller differences found between older male and female participants.

3.4. *Electromyographic-based measures*

During shoulder abduction, rates of EMG-amplitude increase varied between 4% per min and 37% per min. The effects of age and gender were not significant, and no two-way interactions were found. EMG spectral measures (MnPF and MdPF) obtained during shoulder abduction exhibited consistently decreasing trends. Older participants had significantly less rapid spectral changes, with a mean difference of roughly 27% between older and younger. The interactive effect of age × effort level was significant, with greater age-associated differences as effort level increased (figure 6). Effects of gender were not evident.

For torso extension, no significant differences were found in EMG changes between the left and right low-back muscles for either amplitude or spectral measures. Further analyses were therefore based on mean values of the bilateral data. Although younger individuals generally had more rapid changes in EMG amplitude, age effects were not significant for the multifidus and only approached significance for the longissimus

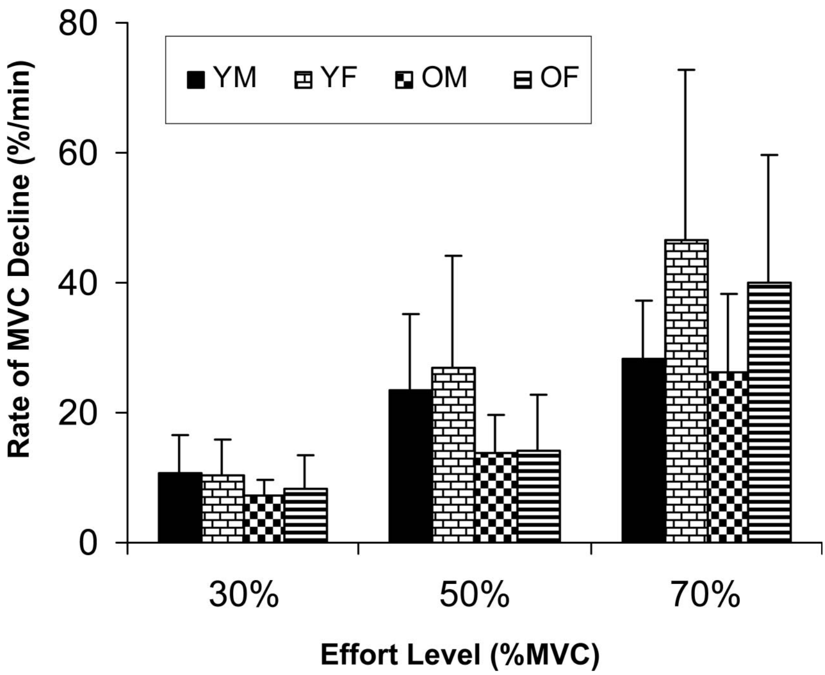


Figure 5. Rates of maximum voluntary contraction (MVC) decline for shoulder abduction, with significant effects of age, effort level and age × gender. Error bars represent standard deviations. YM = younger male; YF = younger female; OM = older male; OF = older female).

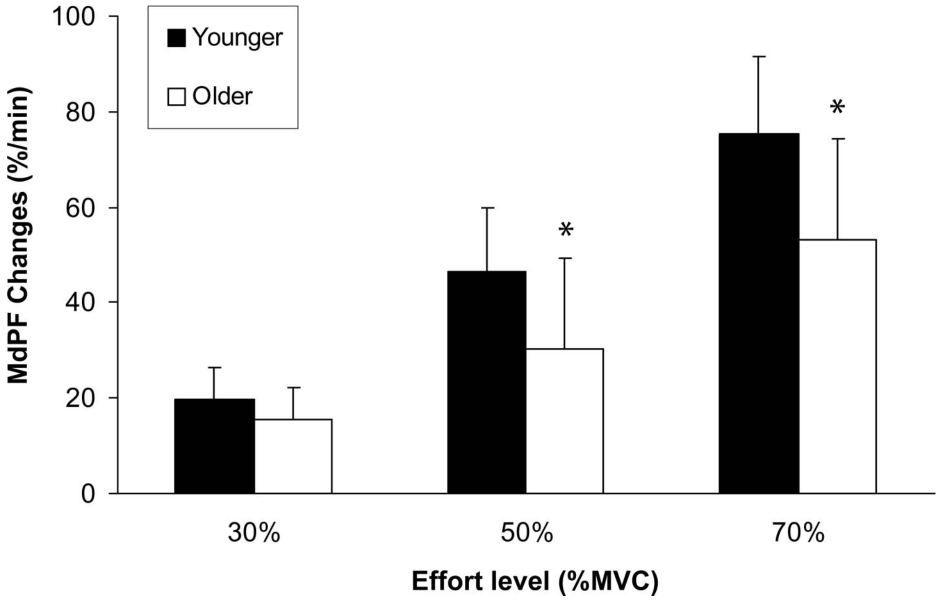


Figure 6. Electromyographic median power frequency (MdPF) changes during shoulder abduction (results similar for mean power frequency), with a significant effect of age × effort level. Error bars represent standard deviations and * indicates significant differences. YM = younger male; YF = younger female; OM = older male; OF = older female).

($p = 0.07$). For both muscles, the interactive effect of age × effort level approached significance ($p = 0.07$). No effects of gender or interactions with gender were present. With regard to changes in EMG spectral measures, the two torso muscles showed similar patterns (figure 7). Less rapid rates of decline were observed for older individuals (about half of those for younger participants). The age × effort level interaction was significant, with greater discrepancies in the slopes between younger and older groups observed as effort levels increased. While an effect of gender as a main effect was not found, its interactive effect with age was significant. This interaction effect showed significantly greater rates of decline for younger males than for the other three groups.

3.5. *Strength recovery*

During the recovery period, a substantial proportion of muscle strength was regained within the first few minutes (figure 8). The magnitude of strength loss at the cessation of both exercises was significantly lower for the older group than for the young, but the difference became non-significant after 10 min for the shoulder abduction and after 2 min for the torso extension. Roughly 75% of trials could be well-fitted using an exponential model; the remaining data showed linear or non-monotonic trends and these were almost equally distributed across age and gender groups. It should be noted that only the well-fitted trials were analysed here. There were no significant age or gender effects on recovery rates in either experiment. The effect of effort level approached significance ($p = 0.07$) for the torso, but only a trend was observed for the shoulder ($p = 0.12$). The effort level effect in both experiments indicated a tendency for faster recovery rates following exercises at lower effort levels.

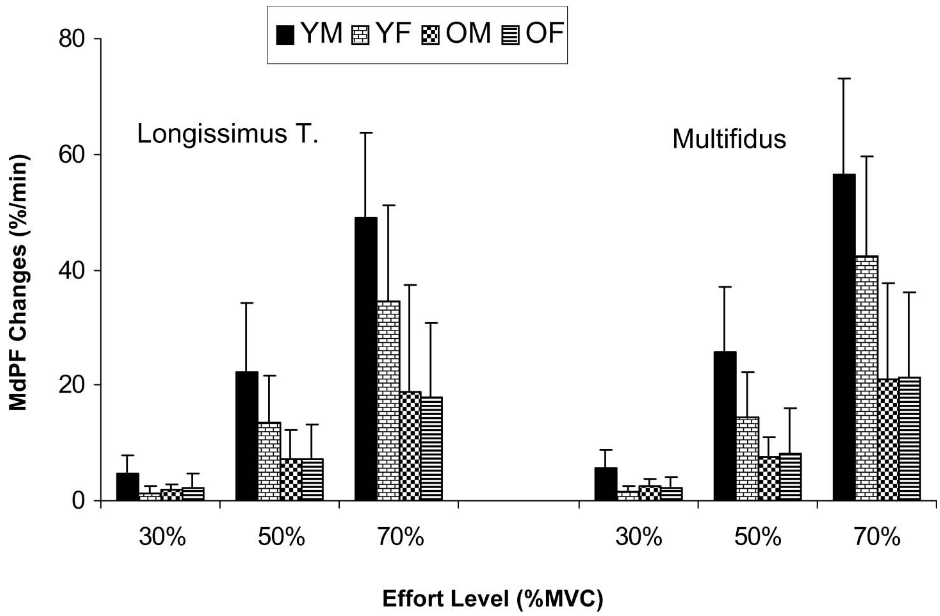


Figure 7. Rates of decrease of electromyographic median power frequency (MdPF) during torso extension (results similar for mean power frequency), with significant effects of age × gender and age × effort level. Error bars represent standard deviations. YM = younger male; YF = younger female; OM = older male; OF = older female; MVC = maximum voluntary contraction.

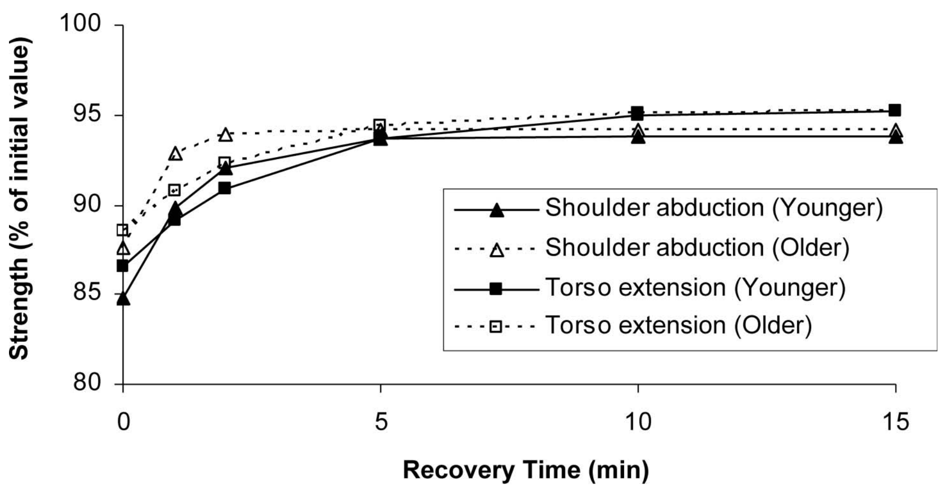


Figure 8. Strength recovery following shoulder abduction and torso extension. Equations for fitted curves are as follows.
Shoulder abduction – Younger: $S = 93.8 - 8.99\ e^{-0.82 * t}$; Older: $S = 94.2 - 6.57\ e^{-1.58 * t}$, Torso extension – Younger: $S = 95.2 - 8.67\ e^{-0.35 * t}$; Older: $S = 95.3 - 6.69\ e^{-0.41 * t}$, where S = strength (%initial), t = time (min).

4. Discussion

The present study aimed to quantify the effects of age on muscle endurance, fatigue and recovery after sustained isometric efforts using two different exercises (shoulder abduction and torso extension). The major findings suggest that older individuals (55–65 years), although exhibiting substantially lower muscle strength, have distinctly increased muscle endurance and less rapid development of local fatigue as compared to younger individuals at comparable levels of relative effort. Differences due to aging were generally more substantial and more consistent during shoulder abductions than lumbar extensions, suggesting a muscle dependency of these age effects.

4.1. *Muscle strength*

Older individuals had about 19% less initial (pre-fatigue) strength in shoulder abduction. This result is comparable to earlier reports using similar exercises and age ranges that showed a difference of 16% (Bäckman *et al.* 1995) and 23% (Hughes *et al.* 1999). A slightly greater difference (27%) in torso extension strength was found between the two age groups. This difference, however, is also comparable to the results of Viitasalo *et al.* (1985), who found that individuals aged 51–55 and 71–75 years had roughly 15% and 35% less torso extension strength, respectively, when contrasted with a younger group (31–35 years).

It is generally accepted that a decline in maximum strength with advancing age occurs after the fifth decade of life (Johnson 1982, Bemben *et al.* 1991, Bäckman *et al.* 1995). This strength decline with aging has been attributed to a reduction in both quality and quantity of excitable muscle mass (Larsson *et al.* 1979, Vandervoort and McComas 1986, Roos *et al.* 1999), primarily due to irreversible fibre damage and a permanent denervation (Brooks and Faulkner 1994, Lexell 1995, Payne and Delbono 2004). The fact that the decline in MVCs in this study differs between muscles is in accordance with earlier observations of variability across muscles (Bemben *et al.* 1991, Lynch *et al.* 1999). Muscle dependency in the age effect may be due, in part, to a more substantial reduction in the use of lumbar extensor muscles with aging (or less habitual use) as compared to the shoulder musculature (Garg 1991, Jørgensen 1997).

Given that the present study focused on endurance and fatigue during participant-specific (relative) effort levels, the results clearly depended on the ability of each participant to exert maximal efforts consistently across experimental sessions. Regardless of age, this requirement appears to be fulfilled by well-trained and motivated healthy individuals (Vandervoort and McComas 1986, De Serres and Enoka 1998, Kent-Braun *et al.* 2002, Lanza *et al.* 2004). More specifically, reports by Kent-Braun *et al.* (2002) and Lanza *et al.* (2004) also indicated no substantial age-related effects in the ability to maximally activate muscles even at the cessation of a fatiguing task. Further evidence of MVC quality is provided by the repeatability of MVCs across days obtained here, as shown by excellent ICC values and relatively small SEMs and CVs.

4.2. *Age-related differences in muscle endurance and fatigue*

The findings related to the presence of age effects in isometric endurance time during shoulder exercise confirmed similar results previously reported (Larsson and Karlsson 1978, Chan *et al.* 2000, Bilodeau *et al.* 2001b). Age-related increases in endurance are generally argued to occur as a result of a change in the proportion of muscle fibre types (i.e. increased type I:type II ratio) that occurs with aging (e.g. Larsson and Karlsson 1978), which in turn is a consequence of selective atrophy of fast-twitch fibres (Lexell 1995). The greater proportion of slow-twitch fibres may result in less lactate accumulation during the type of prolonged efforts studied here (Larsson and Karlsson 1978). It should be noted that muscle metabolic aspects such as substrate availability and oxidative capacity may also affect muscle fatiguability (Bemben 1998), and aging processes affecting such metabolic activities have been suggested to vary across muscles depending on muscle morphology, utilization of the muscle and metabolic demands (Pastoris *et al.* 2000). It can only be speculated that this variance in fibre composition may explain the disparity in the age-related effects on fatiguability between shoulder and torso muscles obtained in the present study.

The older group also showed slower declines in EMG spectral measures and similar findings have been reported in several earlier studies (Merletti *et al.* 1992, Yamada *et al.* 2000, Merletti *et al.* 2002). This effect is likely a consequence of the higher proportion of slow-twitch fibres in older muscles (Merletti *et al.* 2002, Macaluso and De Vito 2004). As noted, a muscle with a predominance of slow-twitch fibres has a lower likelihood of lactate accumulation and acidosis (Brody *et al.* 1991, Kupa *et al.* 1995, Yamada *et al.* 2000). Therefore, a lower rate of decline in muscle fibre conduction velocity and EMG spectral measures can be expected (Mannion *et al.* 1998, Merletti *et al.* 2002). In addition, an interactive age × effort level was found in the present study, with a more considerable difference observed at higher effort levels. As speculated by Bazzucchi *et al.* (2005), this phenomenon could be explained by a relatively greater recruitment of fast-twitch muscle fibres among younger individuals at higher effort levels. In contrast to EMG spectral measures, less consistent results were obtained for EMG amplitude (RMS). This finding may be partly explained by age-related variations in motor unit behaviours in generating different levels of effort (Gerdle *et al.* 1997).

A delayed development of fatigue among older individuals was also supported by the lower rates of MVC decline, with this measure often considered as the 'gold standard' for fatigue assessment (Vøllestad 1997). Rates of MVC decline were lower for the older group in both experiments, although the effect was only substantial for the shoulder. In some cases, the effects of age on fatigue were moderated by gender (age × gender interaction). This interactive effect was found to be substantial for rates of MVC decline during shoulder abduction and for rates of EMG spectral changes during torso extension. Both muscles demonstrated greater gender-related effects for younger subjects. The existence of an age × gender interaction effect on muscle fatiguability has previously been documented by Ditor and Hicks (2000) and Hunter *et al.* (2004), although the effect was found for different measures. This interactive effect could be due to a mixed influence of muscle histology, sex hormones and muscle capillarization (Ditor and Hicks 2000). However, it is not clear why this effect was inconsistent across muscles and across dependent measures.

4.3. *Muscle endurance at relative vs. absolute loads*

It should be noted that effort levels examined here were relative (i.e. normalized against an individual's MVC), and it is therefore not known whether the observed age effects on endurance might also be present if absolute effort levels had been used. As indicated by Larsson and Karlsson (1978), an age-related decline in muscular endurance may be expected at comparable absolute loads due to age-associated reduced muscle strength resulting in an increased relative load in older individuals. Interestingly, however, a recent study using strength matched individuals to examine age-associated difference during sustained elbow flexion showed otherwise (Bazzucchi *et al.* 2005). Although a somewhat small cohort of subjects was recruited (six per age group), older individuals were found to have more resistance to fatigue based on endurance time and EMG measures. In contrast, the present study involved a relatively large number of participants with a goal of minimizing several participant-related confounding factors and increasing external validity.

The results in this study also allowed for examination of the relationships between endurance time and absolute torque, which were found to differ between muscles (as shown in figure 4). During shoulder abductions, the results suggest a marginal effect of age and similar abilities between younger and older females in performing the task, even at an absolute load. However, the results were different for the torso, where lower endurance times were found among older individuals at a similar load magnitude. These results, again, support the existence of muscle dependency in the age effect on muscle performance that may stem from differences between the shoulder and torso muscles in terms of muscle fibre type composition and atrophy rate. Such a muscle dependency should be considered in real world applications, for example, in designing appropriate tasks for older individuals.

4.4. *Age effects on strength recovery*

For both experiments, muscle strength was substantially regained within the first few minutes after cessation of activity. Several studies have found similar exponential patterns of strength recovery following a sustained effort (e.g. Clarke and Stull 1969, Elfving *et al.* 2002) and this pattern has also been found for EMG-based parameters and subjective ratings of perceived fatigue (Baker *et al.* 1993, Elfving *et al.* 2002). The present results indicate that age-related effects on the rate of strength recovery from sustained isometric exercise may be only marginal. Both age groups also demonstrated similar incomplete strength recovery (approx. 95%) at 15 min of recovery. Non-significant age-related effects on recovery rates have previously been reported after fatiguing elbow flexions at intermittent (Allman and Rice 2001) and at maximum (Bilodeau *et al.* 2001a) efforts. It appears that recovery from metabolic inhibition, which is mainly responsible for fatigue during a short sustained contraction, may not show age-related effects in the present study because of the use of normalized loads (Allman and Rice 2001). Different age effects might be expected after a longer duration exercise, using lower effort levels or a different exercise type, since such efforts might result in substantial peripheral failure at the level of excitation–contraction coupling (Baker *et al.* 1993).

4.5. *Task design Implications*

Results of this study highlight the importance of carefully assigning tasks to workers of different ages. While older workers may not have the required capacity for physically challenging tasks, they may be able to perform much lighter tasks for substantially longer periods of time. This approach also ensures job requirements that are well within workers' capacity, which in the long term may reduce the risks of musculoskeletal problems and symptoms. Effort level and gender were also found to influence the relationship between aging and local fatigue. An interaction effect between age $\times$ effort level implies that a relatively small increase in external workload, for example, may have more severe fatigue responses among younger vs. older workers. Similarly, the presence of an age × effort level interaction, although only found in a subset of measures, suggests that tasks assigned to younger and older female workers may not result in substantial performance differences, compared to circumstances where such tasks are allocated to younger and older male individuals. In short, ergonomists should consider these task and individual factors simultaneously when designing/evaluating occupational activities. Finally, as aging effects seem to be muscle dependent, muscle characteristics (e.g. habitual use and fibre type composition) also need to be taken into account. For instance, tasks requiring substantial levels of shoulder exertion may be more appropriate for older workers than ones involving the torso musculature.

4.6. *Study limitations*

A few limitations in the present study warrant discussion. Pure isometric efforts in a controlled posture, as studied here, may have little relevance in terms of the demands of daily living or occupational tasks. Instead, muscle activities are more typically performed dynamically with different postures adopted and different muscles activated with varying motor unit recruitment strategies. The use of isometric efforts, however, allowed for control of numerous sources of variability associated with dynamic efforts and ongoing work is addressing age effects using repetitive isokinetic efforts of the same muscles. Only two tasks were examined in this study, involving a limited number of muscles. As noted above, these tasks were selected because of differences in fibre type composition and function of the muscles involved. Results obtained here may therefore represent extreme cases of muscle dependency in the influence of age on muscular performance. During shoulder abductions, only the middle deltoid was monitored via EMG. Other synergistic muscles (e.g. supraspinatus) may also be involved during such exercises and could provide additional information about fatigue development, but recording the responses of such synergistic muscles would require more complicated signal acquisition procedures. Sole focus on the deltoid muscle EMG was based on its assumed dominant contribution to torque generation during these tasks.

5. Conclusions

Age is a critical factor affecting an individual's physical capacity. Compared to younger participants, older individuals exhibited decreased maximum muscular strength, longer endurance times and slower progressions of local fatigue, but showed little difference in rates of recovery. With regard to fatigue, the age effect was shown to be influenced by effort level, with more pronounced effects observed as the workload increased. Age effects also appear to be muscle dependent, with more substantial differences found at the middle deltoid when compared to lumbar extensor muscles. Effects of gender were found to be less substantial than age, but an interactive effect of gender with age on fatigue was found in some cases. Further work is warranted to determine if similar effects are present among other muscles, among different age groups and during more complex dynamic efforts.

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