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Effects of aging on muscle mechanical function and muscle fiber morphology during short-term immobilization and subsequent retraining

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Hvid L, Aagaard P, Justesen L, Bayer ML, Andersen JL, Ørtenblad N, Kjaer M, Suetta C. Effects of aging on muscle mechanical function and muscle fiber morphology during short-term immobilization and subsequent retraining. *J Appl Physiol* 109: 1628–1634, 2010. First published September 23, 2010; doi:10.1152/japplphysiol.00637.2010.—Very little attention has been given to the combined effects of aging and disuse as separate factors causing deterioration in muscle mechanical function. Thus the purpose of this study was to investigate the effects of 2 wk of immobilization followed by 4 wk of retraining on knee extensor muscle mechanical function (e.g., maximal strength and rapid force capacity) and muscle fiber morphology in 9 old (OM: 67.3 ± 1.3 yr) and 11 young healthy men (YM: 24.4 ± 0.5 yr) with comparable levels of physical activity. Following immobilization, OM demonstrated markedly larger decreases in rapid force capacity (i.e., rate of force development, impulse) than YM (~20–37 vs. ~13–16%; $P < 0.05$). In contrast, muscle fiber area decreased in YM for type I, IIA, and IIx fibers (~15–30%; $P < 0.05$), whereas only type IIa area decreased in OM (13.2%; $P < 0.05$). Subsequent retraining fully restored muscle mechanical function and muscle fiber area in YM, whereas OM showed an attenuated recovery in muscle fiber area and rapid force capacity (tendency). Changes in maximal isometric and dynamic muscle strength were similar between OM and YM. In conclusion, the present data reveal that OM may be more susceptible to the deleterious effects of short-term muscle disuse on muscle fiber size and rapid force capacity than YM. Furthermore, OM seems to require longer time to recover and regain rapid muscle force capacity, which may lead to a larger risk of falling in aged individuals after periods of short-term disuse.

myofiber; disuse; unloading; rate of force development; muscle strength

IT IS WELL KNOWN THAT AGING markedly affects muscle mechanical function (for recent reviews, see Refs. 4, 38). Further maximal muscle strength is a strong predictor of functional status and the ability to maintain independent living in older individuals (28, 30, 31, 39). Importantly, however, maximal leg extension power and rapid muscle force capacity [e.g., rate of force development (RFD)] have been shown to decline to a greater relative extent than maximal muscle strength with aging (cf. Refs. 20, 22, 29, 33) and has been advocated to be of even greater importance for the observed decline in functional status, especially for the ability to counteract unexpected perturbations during walking and/or avoiding falling (3, 18, 30, 35, 40).

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Similar to the long-term effects of aging, short-term muscle disuse has been found to also have a substantial detrimental influence on muscle mechanical function, and, depending on the model and duration of disuse, marked decreases in maximal leg strength (6, 7, 13, 14, 16, 17, 19, 23, 25, 41) and rapid force capacity (6, 13, 23) have been reported. However, the far majority of these studies were carried out in young individuals (cf. Refs. 13, 17, 25).

Thus, in contrast to the vast amount of studies that have looked into aging and disuse as separate factors causing deterioration in muscle mechanical function, very little attention has been given to the combined effects of aging and disuse, as only a single study, apart from our own group (37), has addressed this aspect so far (14). The lack of such information in elderly individuals is striking, considering the future demographic prospects of an increased proportion of elderly in the general population, as well as the fact that old individuals are frequently exposed to periods of muscle disuse caused by disease or injury, eventually leading to hospitalization (Ref. 12, for review, see Ref. 36).

As suggested by injury-related long-term studies, disuse may exacerbate the age-related detrimental effects on knee extensor muscle mechanical function, i.e., leading to amplified losses in maximal strength and rapid force capacity (15, 35). In support of this notion, recent data by Deschenes et al. (14) suggest that healthy old individuals may be more susceptible to short-term disuse than young subjects, by demonstrating more marked impairments in fast dynamic muscle strength. In line with these findings, our laboratory has previously reported that immobilization had a greater impact on the magnitude of neuromuscular activation (assessed by superimposed twitch analysis) in old compared with young individuals (37). Since rapid force capacity has been linked with high levels of fast dynamic (concentric) muscle strength (1) and efferent neuromuscular drive (3, 20), it may be speculated that rapid force capacity would be particularly compromised in old individuals in response to short-term disuse. In addition, our laboratory has also previously reported that old individuals showed an attenuated response to retraining after immobilization compared with young individuals (37), which is supported by findings from animal studies (42).

The purpose of the present study was, therefore, to investigate the effects of 2 wk of muscle disuse (lower limb cast immobilization) followed by 4 wk of retraining on parameters of knee extensor muscle mechanical function, e.g., maximal muscle strength and rapid force capacity, in old and young healthy individuals with comparable levels of physical activity. To determine possible age-related differences in the adaptive response(s) to disuse and subsequent retraining, maximal isometric knee extensor strength normalized to quadriceps muscle volume (mVol) and muscle fiber morphology was investigated. Given that morphology of especially type II muscle fibers and rapid force capacity have been shown to be associated (11, 21, 22, 26), the potential interaction between these parameters was also examined. It was hypothesized that old individuals would be more susceptible to the detrimental effects of disuse on rapid muscle force capacity and that old individuals would show an attenuated recovery in muscle mechanical function due to an attenuated ability to regain muscle mass.

MATERIAL AND METHODS

Subjects

Twenty healthy men, 9 old (OM: 67.3 ± 1.3 yr, 178.7 ± 2.6 cm, 84.8 ± 3.4 kg) and 11 young (YM: 24.4 ± 0.5 yr, 181.4 ± 1.8 cm, 72.2 ± 2.3 kg), volunteered to participate in the study. The sample size was based on power analysis ($\beta = 0.80$) of the expected changes (10%) in maximal isometric knee extensor strength. However, as the variability of different measures of muscle mechanical function deviates (see RESULTS), future studies may benefit from determining sample size based on the outcome parameters that show the greatest variance. Before immobilization, there was no difference in body weight between OM and YM, whereas OM had a larger percentage of body fat than YM (37). No weight changes occurred during the study period. To minimize potential differences in physical activity as a confounding variable, we included subjects with similar activity levels (OM: 5.2 ± 1.4 h/wk; YM: 5.0 ± 0.9 h/wk), assessed by using an occupational and recreational activity questionnaire (32). None of the subjects had previously participated in systematic resistance training.

All subjects underwent medical evaluation, including review of previous medical history and physical examination before participation, and none had a previous record of acute or chronic illness or took any medication affecting skeletal muscle function. All subjects were informed of the risks associated with the investigation and provided their written, informed consent. The study (KF01–322606) was approved by the local Ethics Committee of Copenhagen, in accordance with the Helsinki declaration.

Experimental Procedure

Familiarization with the testing procedures was carried out in separate sessions ~2 wk before the start of the study. All subjects underwent 2 wk of lower limb cast immobilization, followed by 4 wk of retraining. Muscle biopsy sampling (see below) and testing of muscle mechanical function was performed on separate days ~1 wk before (Pre) and 24 h after immobilization (Post), as well as 48 h after retraining (Train). Subjects were instructed not to engage in any vigorous activities 24 h before a test session. Following muscle biopsy sampling, each test session included assessment of body height and weight, as well as measurements of selected parameters of knee extensor muscle mechanical function, which was always preceded by a brief low-intensity warm-up on a cycle ergometer (5 min, 50–150 W). To minimize the influence from diurnal variation, each subject was tested at the same time of day (±2 h).

Immobilization

The immobilization procedure has previously been described in detail (37). In brief, immobilization was accomplished by unilateral whole leg casting (randomly selected limb) using a lightweight cast (X-lite, Allard) with the knee joint fixed at an angle of 30° (0° = full extension). The cast was not removable at any time during the immobilization period. Subjects were carefully instructed to perform all ambulatory activities on crutches, to abstain from ground contact, and to refrain from performing muscle contractions in the immobilized leg. To avoid iatrogenic, muscular, and vascular implications, we kept daily contact with the subjects throughout the immobilization period. Furthermore, to reduce the potential risk of venous thrombosis, subjects were informed to perform isolated, unloaded plantar and dorsal ankle flexions in the immobilized leg several times a day (9, 34).

Retraining

After removal of the cast (and muscle biopsy sampling), subjects received manual mobilization of their immobilized leg by a physiotherapist. This was carried out to ensure that minimal pain was present and that normal range of motion could be obtained at the knee joint. Retraining began 2 days after cast removal and consisted of 4 wk of unilateral strength training of the immobilized leg (3 sessions/wk) to yield a total of 12 training sessions. None of the subjects missed any training sessions (= 100% compliance). All training sessions were supervised, and subjects were continuously provided with feedback on the performed exercises. After adequate warm-up, subjects performed knee extension, leg press, and knee flexion in load-adjustable machines (Technogym International). Loading intensity was 3–4 sets × 12 repetitions (reps) [at 15 repetitions maximum (RM)] in *week 1*, followed by 5 sets × 10 reps (at 12 RM) in *weeks 2* and *3*, and 4 sets × 10 reps (at 12 RM) in *week 4*. Training loads were progressively adjusted in the first training session of each week by use of 5-RM tests, from which the 1-RM load was estimated, and subsequently the training load (12 or 15 RM) was calculated. Subjects were instructed to use moderate (~1–2 s) and slow speed (~3–4 s) in the concentric and eccentric contraction phases, respectively.

Muscle Mechanical Function

Maximal isometric and dynamic muscle strength. As described in detail elsewhere (3, 35), maximal voluntary knee extensor strength was measured using an isokinetic dynamometer (Kinetics Communicator, Chattecx), with all measurements being gravity corrected (3).

After several preconditioning and specific warm-up trials, subjects performed a number of maximal dynamic knee extensions (i.e., concentric contractions) at slow angular speed (60°/s) and were encouraged to exert maximal force (~torque) throughout the entire range of motion (90 to 10°; 0° = full extension). Successive trials were performed until the subject was unable to increase peak torque and area under the torque-angle curve. The trial with the largest contractile work was selected for further analysis. Subsequently, three maximal isometric knee extensions were performed at a knee joint angle of 70°, in which the subjects were instructed to contract as fast and forcefully as possible (3, 11) and maintain maximal force exertion for ~2–3 s (35). The trial with the highest peak torque was selected for further analysis of maximal isometric strength [maximum voluntary contraction (MVC)], rapid force capacity (RFD, impulse), and contraction time parameters. During all test contractions, strong verbal encouragement was given to the subject, along with an online visual display of the dynamometer force signal on a personal computer screen. All knee extension trials were separated by a 1-min rest period.

Onset of contraction was defined as the instant when force production exceeded the baseline level force by 3% of the maximal force value. Any trials with a visible initial countermovement were discarded (3). Individual dynamometer settings were registered to ensure identical subject positioning at all test points (Pre, Post, and Train). Parameters of maximal muscle strength and rapid force capacity were normalized to body mass, thus being indicative of how well an individual would cope with whole body movement tasks. In addition, maximal isometric muscle strength was normalized to quadriceps mVol to also gain information about the qualitative changes in muscle mechanical function. Data on quadriceps mVol data have been reported elsewhere (37).

Rapid force capacity and contraction time parameters. Rapid muscle force capacity, evaluated as contractile rate of force (torque) development (RFD), contractile impulse, and relative RFD (relRFD), as well as contraction time parameters, were determined from the trial with the highest isometric force production, as described in detail previously (3, 35). In brief, contractile RFD was derived as the average tangential slope of the torque-time curve (Δtorque/Δtime) calculated over time intervals 0–50 and 0–100 ms relative to the onset of contraction, i.e., initial and later phase, respectively. Contractile impulse was determined as the area under the torque-time curve (∫torque d*t*) in the same time intervals. In addition, relRFD was calculated by expressing absolute RFD values relative to maximal isometric strength. Contraction time parameters were obtained as the time to reach one-sixth, one-half, and two-thirds of MVC from onset of contraction, respectively.

Muscle Biopsy Sampling and Analysis

Muscle samples were obtained from the middle portion of *m. vastus lateralis*, utilizing the percutaneous needle biopsy technique (8) by the same investigator. Following both intervention periods, efforts were made to extract tissue from the same depth and location (within ∼1–2 cm). After dissecting the muscle samples of all visible blood and adipose and connective tissue, samples were oriented in embedding medium (Tissue-Tek), frozen in isopentane cooled with liquid nitrogen, and stored at −80°C. Subsequently, serial transverse sections (10 μm) were cut in a cryotome at −20°C and stained for myofibrillar ATPase at pH 9.4 after both alkaline (pH 10.3) and acid (pH 4.3 and 4.6) preincubations (10). All samples of each individual subject were stained in the same batch to avoid interassay variation. Muscle fiber type and size were assessed in a blinded fashion with an average of 387 ± 22 fibers analyzed in each biopsy. As previously described (5), muscle fibers were characterized as type I, IIa, or IIx based on the ATPase staining pattern. For the determination of muscle fiber size, only truly horizontal fibers were included, in a minimum of 100 fibers. A videoscope consisting of an Olympus BX 50 microscope (Olympus Electronic, Japan) and a Sanyo high-resolution color video camera (Sanyo Electronic, Japan), in combination with Tema Image-analyses System (Scanbeam, Denmark), were used to calculate the mean fiber cross-sectional area of each fiber type (5). Muscle fiber morphology analysis included determination of fiber-type cross-sectional area, percent number, and percent area. In addition, correlation analysis was performed to examine potential interactions between muscle fiber morphology and RFD (representative of rapid force capacity). This also included the relative (percentage) changes for these parameters in OM and YM separately. For this analysis, type IIa and IIx fiber results were pooled, to yield the combined type II fiber area, percent number, and percent area.

Statistical Analysis

Nonparametric tests were used for statistical analysis, since not all data were normally distributed. Within-group changes due to immobilization and/or retraining were evaluated by the Friedman analysis of variance by ranks, with subsequent analysis using the Wilcoxon signed-rank test for paired samples. Between-group differences were evaluated by the Kruskal-Wallis signed-rank test. Correlations were evaluated using the Spearman's rho rank order correlation (r_s) test. Data are given as means ± SE, and the level of statistical significance was set at $P \leq 0.05$.

RESULTS

Maximal Isometric and Dynamic Muscle Strength

Before immobilization, maximal isometric and dynamic knee extension strength were lower in OM than YM (40 and 42%, respectively; $P < 0.05$) (Table 1). A similar pattern was evident for maximal isometric strength per mVol (27%; $P < 0.05$) (Table 1). After immobilization, maximal isometric and dynamic knee extensor strength decreased to a similar extent in OM (15.5 and 25.6%, respectively; $P < 0.05$) and YM (15.4 and 23.0%, respectively; $P < 0.05$). Maximal isometric strength per mVol decreased in OM (15.6%; $P < 0.05$), while tending to decrease in YM (7.5%; $P = 0.062$). The observed changes did not differ between OM and YM (see Fig. 2).

After retraining, maximal isometric and dynamic strength increased in both OM and YM ($P < 0.05$) and were comparable to values obtained before immobilization (Table 1).

Table 1. *Maximal isometric and dynamic knee extension muscle strength obtained before and after 2 wk of immobilization and after 4 wk of retraining in young and old men*

	YM	OM
Isometric strength		
Per body mass, Nm/kg		
Pre	3.04 ± 0.16	1.77 ± 0.14§
Post	2.56 ± 0.14*	1.50 ± 0.15*§
Train	2.94 ± 0.18§	1.72 ± 0.14†§
Per muscle volume, N/cm²		
Pre	12.64 ± 0.83	9.19 ± 0.81§
Post	11.58 ± 0.71	7.76 ± 0.76*§
Train	12.19 ± 0.68	9.01 ± 0.69†§
Dynamic strength per body mass, Nm/kg		
Pre	2.38 ± 0.15	1.43 ± 0.11§
Post	1.79 ± 0.10*	1.06 ± 0.12*§
Train	2.35 ± 0.12§	1.32 ± 0.13†§

Values are means ± SE; $n = 11$ young men (YM) and $n = 9$ old men (OM). Pre, before 2 wk of immobilization; Post, after 2 wk of immobilization; Train, after 4 wk of retraining. Significantly different from *Pre and †Post: $P < 0.05$. §OM significantly different from YM: $P < 0.05$.

Rapid Muscle Force Capacity

Before immobilization, the torque-time curves recorded during maximal isometric knee extension were less steep in OM than YM (Fig. 1), as manifested by lower RFD and impulse in OM than YM (range 40–43%; $P < 0.05$) (Table 2). However, no age-related differences were seen in relRFD (Table 2).

Isometric torque-time curves were less steep after the period of immobilization in both YM and OM (Fig. 1). Consequently, RFD and impulse decreased in OM during the initial phase of muscle contraction (0–50 ms) (36.2 and 37.1%, respectively; $P < 0.05$), as well as in the later phase (0–100 ms) (24.9 and 33.3%, respectively; $P < 0.05$) (Table 2). These changes were accompanied by a drop in relRFD (20.4 and 8.5%, respectively; $P < 0.05$) (Table 2). In YM, RFD and impulse decreased only during the later phase of muscle contraction (0–100 ms) (15.7 and 12.6%, respectively; $P < 0.05$), while relRFD remained unaltered (Table 2). The observed relative changes (reductions) were greater in OM than YM, both during the initial (0–50 ms: RFD, impulse, relRFD; $P < 0.05$) and later phase of muscle contraction (0–100 ms: RFD; $P = 0.067$, impulse; $P < 0.05$) (Fig. 2, Table 2).

After retraining, the slope of the knee extension torque-time curve increased in both OM and YM (Fig. 1). This was reflected by gains in initial and later phase RFD, impulse, and relRFD to reach values comparable to those observed before immobilization, except for initial phase (0–50 ms) RFD and impulse in OM, which tended ($P = 0.082$) to remain reduced (Table 2).

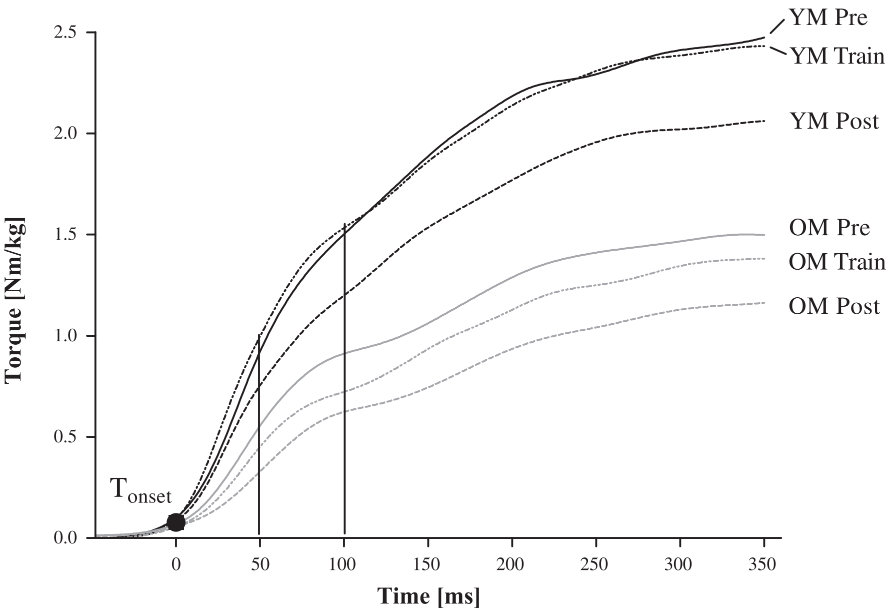

Fig. 1. Group mean torque-time curves obtained during maximal isometric knee extension before (Pre; solid line) and after 2 wk of immobilization (Post; dashed line) and after 4 wk of retraining (Train; dash-dotted line) in young (YM; $n = 11$) and old men (OM; $n = 9$). Solid circle denotes onset of contraction (time $t = 0$ ms); vertical lines denotes time intervals of 50 and 100 ms relative to onset of contraction.

Contraction Time Parameters

Contraction time parameters did not differ between OM and YM before immobilization. Except for an increased time to reach two-thirds MVC in YM following immobilization (16.2%; $P < 0.05$), and a decreased time to reach one-sixth MVC in OM with retraining relative to postimmobilization ($P < 0.05$), no changes were observed in the time to reach one-sixth MVC (OM: Pre 38.3 ± 7.9, Post 44.4 ± 4.0, Train 39.6 ± 4.9 ms; YM: Pre 34.4 ± 4.4, Post: 32.4 ± 4.2, Train: 30.2 ± 4.2 ms), one-half MVC (OM: Pre 112.1 ± 24.7, Post 146.6 ± 13.3, Train 138.8 ± 17.6 ms; YM: Pre 110.2 ± 18.6, Post 110.2 ± 18.6, Train 109.7 ± 10.8 ms), or two-thirds MVC (OM: Pre 179.3 ± 30.5, Post 234.2 ± 20.1, Train 209.5 ± 25.7 ms; YM: Pre 181.4 ± 24.5, Post 209.5 ± 33.1, Train 164.4 ± 15.3 ms). However, the time to reach one-sixth MVC increased to a greater relative extent in OM than in YM with immobilization ($P = 0.010$).

Muscle Fiber Area, Percent, and Percent Area

Before immobilization, type IIx muscle fiber area was smaller in OM vs. YM (31.9%, $P < 0.05$), whereas no differences were seen for type I and IIa fiber area (Table 3). After immobilization, type I, IIa, and IIx fiber area decreased in YM (15.2, 25.8, and 29.7%, respectively; $P < 0.05$), while in OM a reduced type IIa area was observed (13.2%, $P < 0.05$), along with a tendency for a reduced type IIx area (18.8%, $P = 0.08$) (Table 3). Following retraining, muscle fiber area of all three fiber types increased in YM ($P < 0.05$), while no changes were observed in OM. However, in both YM and OM, post-training values were comparable to (i.e., not statistically different from) those observed before immobilization (Table 3). Furthermore, the relative changes induced by immobilization or retraining did not differ between YM and OM. No differences were observed in type I, IIa, or IIx fiber distribution (percent number, percent area) between YM and OM before

Table 2. *Rapid muscle force capacity obtained during maximal isometric knee extension before and after 2 wk of immobilization and after 4 wk of retraining in young and old men*

	YM		OM	
	0–50 ms	0–100 ms	0–50 ms	0–100 ms
RFD, $Nm \cdot s^{-1} \cdot kg^{-1}$				
Pre	16.2 ± 2.3	14.0 ± 1.4	9.6 ± 1.8§	8.4 ± 1.3§
Post	13.3 ± 1.5	11.1 ± 0.9*	5.4 ± 0.9*§	5.7 ± 0.8*§
Train	18.1 ± 2.4†	14.5 ± 1.6†	7.8 ± 1.4†§	6.6 ± 0.7†§
relRFD, %MVC/s				
Pre	527 ± 68	456 ± 39	548 ± 91	480 ± 62
Post	522 ± 49*	436 ± 27	336 ± 34*§	373 ± 28*
Train	610 ± 63†	492 ± 40†	459 ± 78†	394 ± 40
Impulse, $Nm \cdot s \cdot kg^{-1}$				
Pre	22.0 ± 2.7	84.2 ± 9.5	12.7 ± 2.1§	50.7 ± 7.8§
Post	19.1 ± 1.9	68.9 ± 6.4*	7.6 ± 1.1*§	32.2 ± 4.7*§
Train	25.9 ± 3.4†	92.1 ± 10.9†	10.6 ± 1.7†§	41.3 ± 5.3†§

Values are means ± SE; $n = 11$ YM and $n = 9$ OM. RFD, rate of force development; relRFD, relative RFD. Significantly different from *Pre and †Post: $P < 0.05$. §OM significantly different from YM: $P < 0.05$.

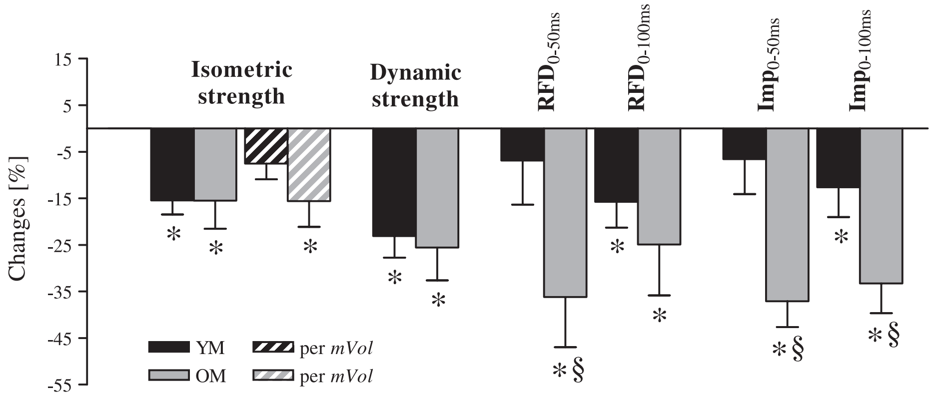

Fig. 2. Relative changes in maximal isometric and dynamic muscle strength, as well as in contractile rate of force development (RFD) and impulse (Imp) during the initial (0–50 ms) and later phase of contraction (0–100 ms) after 2 wk of immobilization in YM (n = 11) and OM (n = 9). Values are means ± SE. mVol, muscle volume. *Significantly different from Pre: $P < 0.05$. §OM significantly different from YM: $P < 0.05$.

immobilization, and no changes occurred with immobilization or retraining in either YM or OM (Table 3).

Relationships between Muscle Morphology and Rapid Force Capacity

While no relationships were observed in OM, type II fiber area (μm²) and initial phase RFD (0–50 ms; $Nm \cdot s^{-1} \cdot kg^{-1}$) were positively related in YM ($r_s = 0.70$; $P < 0.05$) before immobilization. No relationships were observed after immobilization and retraining, respectively. Furthermore, no relationships were observed between RFD and type II fiber percent number or percent area at any time point. Finally, no associations were observed between relative (percentage) changes in RFD vs. relative changes in type II fiber area, percent number, or percent area, respectively, following immobilization or retraining.

DISCUSSION

The present study investigated the effects of short-term disuse (unilateral lower limb cast immobilization) and subsequent retraining on knee extensor muscle mechanical function (including maximal muscle strength and rapid force capacity) and muscle fiber morphology in old (OM) vs. young (YM) individuals. To the best of our knowledge, no previous study has examined the concurrent change in rapid force capacity and muscle fiber morphology in response to short-term disuse and subsequent recovery in old and young healthy individuals.

The main findings were that rapid muscle force capacity during the initial phase of muscle contraction was markedly more affected in OM than in YM following immobilization, and that OM showed signs of impaired recovery in muscle fiber size and rapid force capacity with retraining compared with YM. Furthermore, the changes in muscle mechanical function with immobilization and subsequent retraining were mediated through different adaptive pathways, as indicated by the larger and smaller changes in muscle fiber size and maximal isometric strength per mVol, respectively, in YM than in OM.

Effects of Immobilization

As expected based on previous findings, markers of muscle mechanical function were markedly reduced in OM compared with YM before immobilization (cf. Figs. 1 and 2, Tables 1 and 2) (11, 18, 20, 21, 24, 26, 27). In the present study, OM and YM demonstrated similar relative losses in maximal isometric and dynamic muscle strength (at a slow contraction velocity) in response to 2 wk of immobilization. This observation corresponds well with findings by Deschenes et al. (14), albeit they reported slightly lower changes in maximal isometric and dynamic knee extensor strength in old and young healthy men after 7 days of lower limb immobilization using a knee brace. The 15.4% drop in maximal isometric muscle strength that was

Table 3. *Muscle fiber type area, percentage number, and percentage area before and after 2 wk of immobilization and after 4 wk of retraining in young and old men*

	YM			OM		
	Type I	Type IIa	Type IIx	Type I	Type IIa	Type IIx
Area, μm²						
Pre	5,180 ± 480	6,073 ± 448	5,458 ± 344	5,301 ± 497	5,029 ± 634	3,715 ± 444§
Post	4,440 ± 500*	4,537 ± 480*	3,891 ± 441*	4,830 ± 587	4,269 ± 545*	2,924 ± 200
Train	5,386 ± 509†	6,033 ± 534†	5,558 ± 465†	4,848 ± 382	4,415 ± 371§	3,542 ± 185§
Percentage number, %						
Pre	55.5 ± 2.9	34.0 ± 3.3	10.5 ± 1.4	56.1 ± 3.5	31.2 ± 3.5	11.7 ± 1.7
Post	50.9 ± 3.8	35.2 ± 3.5	13.9 ± 3.2	49.8 ± 4.0	35.4 ± 3.9	14.8 ± 2.8
Train	50.5 ± 4.7	39.2 ± 3.9	10.3 ± 2.0	54.7 ± 6.9	31.2 ± 3.4	14.1 ± 4.0
Percentage area, %						
Pre	53.8 ± 3.4	37.2 ± 3.9	8.3 ± 1.6	61.0 ± 5.9	30.0 ± 5.6	9.0 ± 1.6
Post	48.9 ± 3.6	39.3 ± 3.5	11.7 ± 2.2	54.8 ± 4.8	32.5 ± 4.7	12.7 ± 2.6
Train	50.3 ± 6.2	38.9 ± 4.6	8.7 ± 2.0	56.8 ± 8.2	29.3 ± 4.5	13.8 ± 4.3

Values are means ± SE; n = 9 YM and n = 7 OM. The reduced number of subjects in this analysis was due to a low quality of the muscle biopsy samples obtained at some time points in some subjects. Significantly different from *Pre and †Post: $P < 0.05$. §OM significantly different from YM: $P < 0.05$.

observed in YM is in agreement with previous reports in young healthy individuals after similar periods of muscle disuse (10–14 days) (6, 7, 13, 25). Interestingly, rapid force capacity (RFD, impulse) was affected at greater extent in OM (~25–37% reduced) than in YM (~13–16% reduced), especially during the initial phase of muscle contraction (0–50 ms). While the aspect of short-term muscle disuse on rapid force capacity has not previously been investigated in healthy old individuals, other data exist to support the present findings. Thus maximal muscle strength declined to a greater extent in old compared with young healthy individuals during fast (120°/s), but not slow (30 and 60°/s), concentric quadriceps contractions following 7 days of immobilization (14), which, given the suggested linkage between a high-contractile RFD and high levels of dynamic muscle strength exerted at fast contraction speeds (1), suggests that rapid force capacity may also have been more markedly affected in their old subjects.

In contrast, cross-sectional area decreased in YM for all three fiber types (~15–30%), in accordance with previous findings (6, 17, 41), whereas only type IIa area (along with a tendency in type IIx) was found to decrease in OM (~13–18%) (Table 3). In a functional perspective, type II fiber area as well as percent number and percent area have been shown to correlate with the ability to perform rapid or explosive-type movements (11, 21, 22, 26). Nevertheless, these findings do not per se implicitly imply a causative relationship. Therefore, the fact that we only observed positive associations between type II muscle fiber area and initial phase (0–50 ms) RFD before immobilization in YM suggests that other factors play an important role as well for rapid force capacity.

Effects of Retraining

In agreement with previous studies using similar periods of muscle disuse and retraining in healthy young individuals, full recovery of maximal isometric and slow dynamic muscle strength was observed (16, 17, 19, 25). Findings from animal studies suggest that the recovery in muscle mechanical function and size after disuse may be impaired at old age (42). This notion was not uniformly supported by the present data, as old and young subjects showed similar recovery in maximal dynamic and isometric muscle strength after 4 wk of retraining. However, signs of attenuated ability to recover in old individuals were observed, as muscle fiber areas did not increase with retraining, and rapid force capacity (RFD, impulse) at the very initial phase of contraction (0–50 ms) tended ($P = 0.08$) to remain reduced relative to baseline levels after retraining. Collectively, these data imply that not all aspects of muscle mechanical function may be completely restored after 4 wk of retraining subsequent to 2 wk of cast immobilization, especially in aging individuals. More information is clearly needed to elucidate whether or not the time course of regaining muscle mechanical function differs between young and old individuals after a short period of disuse, as well as to determine how preventive and rehabilitative (strength training) approaches should be designed.

Adaptive Mechanisms

The present changes in muscle mechanical function due to immobilization and subsequent retraining could, in part, be ascribed to changes in muscle mass, although the fact that muscle fiber area seemed less affected in OM than in YM during both immobilization and retraining, along with a more pronounced decline in rapid force capacity in OM compared with YM, suggests that different adaptive mechanisms may be involved in young vs. old healthy individuals. In accordance with the greater relative loss and subsequent gain in muscle fiber area as well as quadriceps mVol (37) in YM following immobilization and retraining, respectively, it was observed that muscle architecture (vastus lateralis fiber pennation angle) was more severely affected in YM than in OM (37). Thus the adaptive change in fiber pennation angle is likely to have contributed to the observed changes in muscle mechanical function (2). In support hereof, similar alterations in muscle architecture recently were observed in young individuals in response to lower limb disuse of comparable duration (13).

In contrast to the observed changes in maximal isometric and dynamic muscle strength, the immobilization-induced decline in maximal isometric strength per mVol, rapid force capacity (RFD, relRFD, impulse), and the time to reach one-sixth MVC were markedly more pronounced in OM than in YM, which may be indicative of greater qualitative changes within the neural system (3, 20) of old individuals. In support of this notion, the level of neuromuscular activation was more severely affected in OM than YM following immobilization (37).

Conclusions

The present data demonstrate a remarkable plasticity in lower limb muscle mechanical function of both old and young individuals in response to short-term disuse (2 wk cast immobilization) and subsequent retraining (4 wk), where elderly subjects showed more marked deteriorations in rapid force capacity and maximal isometric strength per mVol, despite a lesser relative loss in muscle fiber size. The proposed adaptive mechanisms by which muscle mechanical function, including rapid force capacity, was altered during immobilization and subsequent retraining seem to differ between YM and OM. Overall, young individuals were more affected within the muscular system, whereas nonmuscular changes (plausible within the neural system) seemed to be more prominent in the elderly.

Concomitant with an accumulating bulk of evidence, including results from our own laboratory (cf. Ref. 35), the present data confirmed that old individuals have a retained, albeit attenuated, ability of adapting to resistance training following disuse, since some signs of impaired recovery were observed in OM after the period of retraining. This stresses the importance of using effective approaches such as resistance exercise of sufficient duration and with high loading intensities in the prevention and rehabilitation of short-term disuse in elderly individuals who are concurrently exposed to the deleterious effects of aging per se on muscle mechanical function and size.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

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