EFFECT OF IMMOBILIZATION ON ANKLE DORSIFLEXION STRENGTH

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This study was performed in order to determine the loss of strength of the dorsiflexors in healthy persons after immobilization of the ankle, and the ability of these muscles to regain strength. First, isometric ankle dorsiflexion strength was measured in 33 healthy male and 39 female subjects in age categories 20–40 and 40–80 years, in order to obtain reference data and to determine the reproducibility of the measurement protocol. Gender, age and ankle position had a significant influence on the ankle dorsiflexion torque. Secondly, torque was measured in 15 patients after 4–6 weeks' immobilization of the ankle due to a fracture. A 28% decrease in dorsiflexion torque was seen. Strength reduction in neutral position and in 30° plantar flexion was not significantly different. Without specific therapy restoration of torque was almost complete 6 weeks after cast removal.

Key words: torque measurement, ankle dorsiflexors, immobilization.

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INTRODUCTION

In patients with a paresis of the dorsiflexors an ankle foot orthosis (AFO) is often prescribed to correct the resulting foot drop and restore walking ability. In clinical practice, two opposing opinions as to the effects of AFO use on the remaining strength and possible restoration of strength exist. One states that AFO use, by early restoration of walking, stimulates muscle synergetic activity and thereby prevents further loss of muscle function. The other opinion is that AFO use impedes ankle movement, causing disuse and, by taking over the ankle dorsiflexion function, reduces the existing dorsiflexor muscle activity. Further weakening of the ankle dorsiflexors and a poorer restoration of strength over time would be the result. The clinical relevance of this dilemma is determined by the susceptibility of the dorsiflexors to immobilization atrophy in general. If immobilization does not cause significant strength reduction, AFO use can theoretically not be harmful. The effects of immobilization on muscle strength have been predominantly described in animal studies (1). Immobilization studies involving human subjects focused mainly on the quadriceps and/or triceps surae muscle (2, 3). The tendency of muscles to weaken during immobilization differs, depending on e.g. muscle type, position and duration of immobilization (4–6). A problem in the evaluation of immobilization effects is that data available on normal torque values of the dorsiflexor muscles vary widely, suggesting dependency on protocol. Therefore, the aim of the first study was to evaluate our protocol, to determine the reproducibility of ankle torque measurements in healthy adults and to collect reference data from 72 healthy volunteers. A second aim was to study the loss of strength and the extent of spontaneous strength recovery of the dorsiflexors in healthy persons after 4–6 weeks of total immobilization of the ankle in neutral position, to determine to what extent strength loss of the ankle dorsiflexors occurs in subjects without neurological problems. From 15 healthy persons who had had an ankle immobilized in a plaster cast because of a fracture of the lower leg, the level of torque reduction immediately after cast removal and torque restoration 6 weeks afterwards were assessed. This was done in a 0° and 30° ankle angle in order to detect a possible difference in strength reduction due to the position of immobilization (0°).

MATERIALS AND METHODS

Subjects

First a reference study was performed to assess the reproducibility of the results measured with the described protocol and to gather reference values. In the reference study, 72 healthy volunteers were included. The group consisted of 33 men and 39 women recruited from staff and healthy visitors of the rehabilitation clinic. Each subject met the following criteria: age between 18 and 80 years, no incidence of fracture, trauma or contractures of the lower limbs and no history of musculoskeletal, reumatological, neurological or orthopaedic problems in the lower extremities that would reduce maximum voluntary contraction (MVC).

In the immobilisation study, 15 persons who had had an ankle immobilized in a weight-bearing cast below the knee following a lower leg fracture, participated. The mean duration of ankle immobilization was 40 (SD = 8) days. The first measurement took place on average 31 (SD = 13) hours after removal of the cast, the second measurement 43 (SD = 3) days later. They all met the following criteria: aged between 18 and 80 years, immobilization of the ankle in neutral position during 4–6 weeks; immobilisation due to a lower leg fracture treated without internal fixation around the ankle; capable of performing measurements without risk of re-injury after cast removal; capable of holding the foot in 0° and 30° plantar flexion unaided; no ankle complaints or ankle fractures in the past year other than the present pathology and no additional history of musculoskeletal, reumatological, neurological or orthopaedic problems regarding the leg.

The demographic data of both groups are given in Table I.

Patients were recruited from regional hospitals. The study was

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Table I. *Group composition in reference study and immobilization study (mean and SD)*

Gender	Category (years)	*n*	Age (years)	Height (m)	Weight (kg)
Reference study					
Male	20–49	20	34.8 (8.8)	1.83 (7.2)	80.1 (10.4)
	50–80	13	66.6 (6.8)	1.77 (5.6)	87.1 (13.4)
Female	20–49	25	32.4 (7.8)	1.68 (5.6)	66.1 (11.1)
	50–80	14	61.0 (5.2)	1.62 (5.2)	70.2 (21.9)
Immobilization study					
Male		6	33.0 (11.1)	1.83 (14.0)	90.5 (28.7)
Female		9	45.7 (8.1)	1.65 (6.4)	79.4 (10.2)

approved by the local medical ethical committee. All patients signed informed consent before entering the study.

Test procedure

In both studies the same test protocol was used. Isometric torque was measured while the subject was in a supine position with the hips slightly flexed and the knee joint angle in neutral (≈0°) position. The upper and lower leg were fixed to the examination table with two velcro straps. The foot was positioned against a small horizontally placed plastic beam (17 × 2 cm) covered with foam rubber, spanning the whole width of the foot at the level of the first metatarso-phalangeal joint (MTP 1). The foot was not supported below the heel, in order to prevent any heel force exerting a moment around the ankle (Fig. 1).

A Tedea-Huntleigh model 601 load cell was used to measure torque. The centre of the beam was in alignment with the centre of the load cell through the use of an U-shaped rigid light weight hook (Fig. 1).

Calibration of the dynamometer was performed under static conditions with a known weight after each complete session. Body weight, height and foot size were registered, and leg dominance was determined by asking participants which leg they preferred for kicking a ball. After 5 minutes warming up on a home trainer, patients and controls were given standardized verbal instruction to pull the foot against the beam with a maximum effort for 5 seconds. No verbal encouragement was given. Visual feedback was given on the relative strength of the contraction by an analogue gauge. Subjects repeated the contractions ten times with 30 seconds interval to prevent fatigue. Measurements took place in 0° and 30° plantar flexion of the ankle in both legs with a 5 minutes pause in between. The sequence of measurements was randomly assigned. After completing ten repetitions in one position the distances between the contact area of the dynamometer with MTP1 and the line connecting the apices of the lateral and medial malleolus, representing the position of the ankle flexion axis, were measured (7). Data acquisition was performed using a 12 bit DT2824 PGL A/D converter board (Data Translation Inc. Marlboro, Mass.) and MUCAPS software (Multi Channel Acquisition and Processing System, iRv, Neth.) with a sample frequency of 500 Hz and a sample time of 10 seconds.

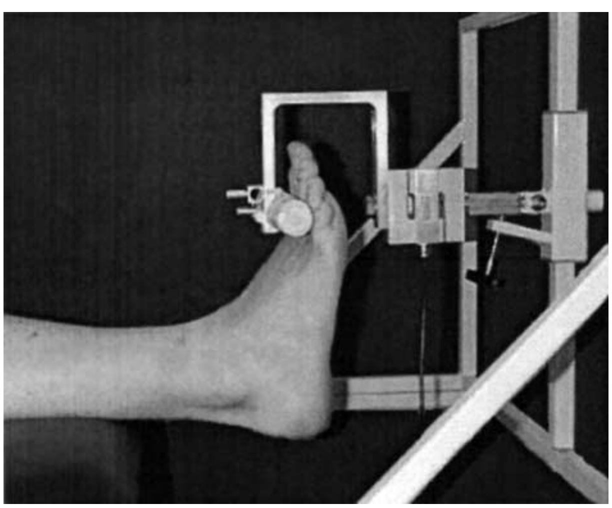

Fig. 1. Isometric dorsiflexor torque measurement with the ankle in neutral position (0°). The plastic beam at the level of the metatarso-phalangeal joints is connected by a U-shaped hook to a load cell.

Data analysis

Strength data were analysed off-line using the MATLAB software package (The Math Works, Natick, Mass.). A 1 second sustained maximum force effort was calculated from the load cell signal for each trial for each subject using a windowing technique. In order to determine the net muscle strength it is necessary to incorporate the effect of the weight of the foot (8). The weight of the foot relative to the total body weight is estimated at 1.4% (9). This process resulted in ten values, corrected for gravity, for each position for each subject. The three highest values for each position were selected and the average of these three values was used as the maximum value for the subject in that position (10). This procedure was performed on both reference and patients data. For each of the four experimental conditions of the reference group a within subject coefficient of variation (CV) was calculated. The CV was calculated by dividing the standard deviation of the three maxima in each block by their mean value. Means and standard deviations were calculated for the maxima of all subjects. Since parametric statistics criteria were met, possible influences in results caused by gender (M/F), age (20–49/50–80), ankle angle (0°/30°) or leg dominance (L/R) in the reference group were each tested using MANOVA and paired *t*-tests with a p-value < 0.05 as limit for significance. Since the number of participants was relatively small for the immobilization group possible differences in torque between the two measurement sessions, i.e. immediately after cast removal and 6 weeks later, were analysed using the Wilcoxon signed ranks test. A similar procedure was performed for the torque production in the two different ankle angles in the latter group. Torque reduction in Table IV is expressed in absolute values (N) and relative (%) to the value of the healthy side in the second measurement. All statistical analyses were performed by means of SPSS software (SPSS Inc., Chicago, Ill.).

RESULTS

Reference study

Reference values of the group of 72 healthy volunteers are presented in Table II. Gender, age and ankle position had a significant influence on the torque produced (p-values between 0.000 and 0.021). Neither left or right side nor presumed leg dominance showed a significant relation to torque production. Therefore, henceforth the average of both torque values is used as reference value.

Table II. *Reference values for dorsiflexor muscle strength (mean (SD))*

Results of torque measurements of 72 healthy volunteers of the ankle dorsiflexor muscles in 0° and 30° plantar flexion of the ankle. Significant differences were found between the two ankle angles, the young and the old group and male and females ($p < 0.05$). No significant differences were found between left or right leg.

				Torque (Nm)		
Angle	*n*	Gender	Age (years)	Right ankle	Left ankle	Both ankles
0°	20	Male	20–49	40.9 (7.4)	42.8 (7.8)	41.8 (7.0)
	13		50–80	26.4 (11.7)	28.0 (12.4)	27.2 (11.3)
	25	Female	20–49	31.5 (6.6)	31.0 (5.9)	31.2 (5.9)
	14		50–80	22.7 (8.0)	21.9 (6.8)	22.3 (7.2)
30°	20	Male	20–49	54.4 (9.5)	54.5 (10.6)	54.4 (9.5)
	13		50–80	45.1 (13.4)	44.4 (10.8)	44.8 (11.7)
	25	Female	20–49	39.5 (6.7)	38.2 (6.3)	38.9 (6.4)
	14		50–80	32.8 (8.7)	31.4 (8.7)	32.1 (8.6)

Table III. *Coefficients of variation (CV) (%) of healthy subjects*

The maximum torque in each position is measured by averaging the three highest values out of ten attempts. The variation between these values are expressed as coefficients of variation.

Ankle position	Minimum	Maximum	Mean (SD)
0° right	0.3	18.2	4.8 (3.7)
0° left	0.2	18.4	4.5 (3.8)
30° right	0.2	16.5	4.1 (4.0)
30° left	0.3	14.6	3.2 (2.7)

Reproducibility

The CVs of the healthy subjects range from 0.2% to 18.4%. In general the lowest CVs result from measurements in 30° (Table III). The mean CV of all measurements was 4.2% (SD = 3.6). Only 7.6% of all within subject CV's exceeded 10%.

Immobilization study

Results of the torque measurements of the patients are displayed in Table IV. All patients completed the measurements. No complications or new injury occurred. The mean torques of the non-injured leg of the patients (Table IV) were in the same range as the reference values of the healthy population (Table II). Immediately after removal of the plaster cast the mean torque values in both positions (0° and 30°) were significantly lower ($p < 0.001$) compared to the non-injured side in measurement two (Table IV), 24% and 31%, respectively.

There was a non-significant slight difference in the relative amount of torque preservation in 0° and 30°, i.e. 76% and 69%, respectively. In both positions the strength of the dorsiflexors of the injured leg increased significantly during the 6 weeks after cast removal ($p = 0.003$ in 0° position and $p = 0.002$ in 30° position). After 6 weeks the strength of the dorsiflexors of the injured leg did not differ significantly from the strength in the non-injured leg.

DISCUSSION

Reference values

The first question of this study was to gather reference data and determine the reproducibility of ankle torque measurements in healthy adults. The absolute values collected in this reference group are in agreement with most other studies (Table V). Only Sepic et al. (11) found higher torque values. Furthermore, in the reference group we found torque values measured in a 0° position to be significantly lower than torque values in a 30°

Table IV. *Relative and absolute mean (SD) dorsiflexor torque in both the injured and non-injured leg in patients (*n *= 15) following a period of ankle immobilisation, immediately after cast removal (measurement 1) and 6 weeks later (measurement 2).*

The relative strength in this table is expressed as a percentage of the strength of the healthy side of measurement two. There was no significant difference between the torque values of the healthy side in measurement one or two and between the amount of torque reduction in the two ankle positions in measurement 1.

		Measurement 1		Measurement 2	
		Injured leg	Non-injured leg	Injured leg	Non-injured leg
0°	Strength (Nm)	24.6 (11.9)*	36.6 (16.2)	33.3 (16.6)	33.7 (12.5)
	Relative strength (%)	76 (32)*	108 (22)	98 (29)	100
30°	Strength (Nm)	29.7 (16.3)*	43.9 (16.5)	41.9 (19.8)	43.5 (15.6)
	Relative strength (%)	69 (27)*	101 (17)	94 (20)	100

* Significant values, $p < 0.001$.

Table V. *Literature values of isometric dorsiflexion strength*

		Torque in Nm (mean and SD)				
Author	Gender	Ankle angle 0°	Ankle angle 30°	Age (years)	*n*	Knee angle
Marsh et al. (13)	M	46.5*	47*	19–37	25	90°, seated
Sepic et al. (11)	M	79.3 (15.4)**		32.0 (2.6)	10	90°, seated
	M	75.6 (13.9)**		56.5 (3.2)	10	
	F	44.7 (8.5)**		29.1 (3.2)	10	
	F	47.3 (11.1)**		54.8 (4.0)	10	
Vandervoort et al. (35)	M		43.5 (6.5)	20–32	11	90°, seated
	M		37.2 (4.3)	40–52	10	
	M		36.2 (7.6)	60–69	13	
	M		31.6 (8.6)	70–79	16	
	M		24.2 (7.0)	80–100	13	
	F		26.6 (4.5)	20–32	11	
	F		25.8 (6.3)	40–52	10	
	F		23.8 (3.1)	60–69	10	
	F		21.5 (3.9)	70–79	16	
	F		16.7 (4.9)	80–100	13	
Vander Linden et al. (14)	M	45.1 (5.9)	45.2 (5.7)	21–35	20	90°, prone
Vandervoort et al. (36)	M	42.9		55–60	20	0°, prone
	M	43.1		61–65	18	
	M	38.8		66–70	18	
	M	36.9		71–75	20	
	M	30.8		76–80	18	
	M	28.7		81–85	17	
	F	27.0		55–60	16	
	F	23.6		61–65	17	
	F	23.6		66–70	17	
	F	22.6		71–75	18	
	F	19.4		76–80	17	
	F	19.0		81–85	18	
Van Schaik et al. (12)	M	38*	52*	20–40	15	90°, seated
	M	32*	43*	60–80	15	
	F	22*	36*	20–40	15	
	F	18*	30*	60–80	15	
Hicks et al. (37)	M		48.1 (12.1)#	60–70	25	90°, seated
	M		47.1 (7.6)#	70–80	19	
	F		29.6 (7.0)#	60–70	28	
	F		26.7 (5.9)#	70–80	37	
Thelen et al. (38)	M		43 (8)#	19–29	12	0°, supine
	M		37 (5)#	65–86	12	
	F		28 (4)#	19–29	12	
	F		22 (3)#	65–86	12	

* Extrapolated from graph; ** Values divided by ten to convert from kgcm to Nm; # = 20° ankle angle; $ = 10° ankle angle; M = male; F = female.

plantar position. These results are in agreement with those found by van Schaik et al. (12). However, Marsh et al. (13) and Vander Linden et al. (14) reported nearly identical torque values in both ankle positions. These conflicting results are probably due to differences in measurement protocols. This stresses the importance of collecting reference values if a different protocol or set up is used.

The reference values showed significant differences in torque production between young and old participants as well as between males and females. No significant differences were found between the left and right leg or in relation to leg dominance. These results are in agreement with most other studies as shown in Table V.

Evaluation of the protocol

The protocol resulted in reproducible values with a mean CV of 4.2% (SD = 3.6). During this study all subjects were asked to complete ten contractions in each position. When selecting the three highest contraction values to calculate the maximum torque we found that in most cases they were produced during the first five efforts. Thus it seems the 30 seconds rest in between did not prevent fatigue. Therefore, the protocol can be improved by using five contractions in each position and a longer pause in between.

Torque reduction after immobilization

The second question we posed was to what extent does strength loss of the ankle dorsiflexors occur after 4–6 weeks immobilization of the lower leg in subjects without neurological problems. This information would give us insight in the susceptibility of this specific muscle group to immobilisation atrophy. Torque reduction after immobilization is mainly due to fibre atrophy, and reduced electromechanical efficiency (2, 15, 16). The human tibialis anterior muscle predominantly consists of type 1 fibres (17, 18). Animal models show a larger sensitivity to strength loss after immobilization in muscles predominantly consisting of type I fibres. The phasic activity of the tibialis anterior muscle on the other hand, might protect against serious torque reduction (4). In the present study the average loss of strength was 28%, irrespective of sex, age or leg dominance. Because all patients were able to perform the contractions without serious discomfort, the lower torque values immediately after cast removal could not be explained by pain or fear. The values of the present study correspond with those found by Tropp & Norlin (19) in isokinetic torque measurements after cast bearing. Other studies (2, 20–23) concerning human muscle response to immobilisation report torque reduction ranging from 59% in the quadriceps muscle (22) to only 8% in the ankle dorsiflexors (20). There are however large differences between the results of these studies, probably due to differences in measurement protocols or subjects. An explanation for the larger amount of torque reduction found in our study and that of Tropp & Norlin (19) is the fact they both measured patients. All other reported studies dealt with healthy (mostly young, male) volunteers. Possibly those healthy subjects involuntary performed isometric contractions in the cast, of which Rozier et al. (24) demonstrated the positive effect for the quadriceps, in contrast to the patients with a fracture who will possibly minimize muscle activity around the ankle due to pain or fear. The same explanation could be applied to explain the lesser torque reduction in bed rest studies. Compared with the above-mentioned results of torque reduction in different muscles, a decline in torque of 28% puts the dorsiflexors of the foot high on the rank of muscles susceptible for disuse.

Ankle joint position during immobilization

A third question posed was whether a difference in strength reduction of the dorsiflexors measured in a 0° and 30° ankle angle could be found immediately after cast removal. Theoretically, the optimum length of the tibialis anterior muscle to generate torque is between 10° and 30° plantar flexion (13, 25). The maximum of this force-length relationship can shift due to morphological changes. In the plaster cast the ankle was immobilised in a neutral position, which means a shortened position for the dorsiflexor muscles. Because a muscle will adapt its number of sarcomeres to a shortened position (6, 26, 27) we expected a decline in torque production (28–31), which would correspond to a shift of the force-length curve to the left. We expected therefore in the first measurement to find the strength loss to be more pronounced in the 30° position. However, torque reduction in 0° immediately after cast removal and 6 weeks later was not significantly different from that in plantar flexion. Tissue changes that might have occurred due to the shortened immobilisation of the tibialis anterior muscle seem to affect the torque production equally in both positions.

Restoration of torque production

The last question was to what extent does spontaneous strength recovery take place during the 6 weeks after cast removal? Spontaneous recovery of function after resuming activities is often reported. Booth (32) and Booth & Seider (33) described a full restoration of torque and fibre composition after 120 days in rats that had been immobilized for 90 days. Witzmann et al. (34) found a complete recovery from 6 weeks immobilization in rats after 4 weeks. Jaweed et al. (23) reported full restoration of strength and fibre composition in human gastrocnemius-soleus muscle in 28 days after a 30 days immobilization period. In our study no significant difference in torque between the injured and non-injured leg was found 6 weeks after cast removal.

CONCLUSION

Human dorsiflexor muscles of the ankle are highly susceptible to strength loss, i.e. 28% in 40 (SD = 8) days of immobilization of the ankle in a weight-bearing plaster cast. Immobilization with the ankle in a neutral position does not seem to affect the optimal length of this muscle group to produce force. After cast removal full recovery takes place within a period of 6 weeks without specific therapy. Given the above-mentioned torque reduction in healthy subjects, for the group of people using an AFO after neurological damage of the peroneal nerve there seems to be a serious risk of further strength loss due to the (partial) immobilization of the ankle. However, whether these results are also applicable to paretic muscles will be subject to further study.

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REFERENCES

1. Musacchia XJ, Steffen JM, Fell RD. Disuse atrophy of skeletal muscle: animal models. Exer Sports Sci Rev 1988; 16: 61–87.
2. Berg HE, Larsson L, Tesch PA. Lower limb skeletal muscle function after 6 weeks of bed rest. J Appl Physiol 1997; 82: 182–188.
3. Veldhuizen JW. Knee immobilization. Thesis. University of Maastricht, 1995.
4. Appell H. Muscular atrophy following immobilisation—a review. Sports Med 1990; 1: 42–58.
5. St-Pierre D, Gardiner PF. The effect of immobilization and exercise on muscle function: a review. Physiotherapy Canada 1987; 39: 24–36.
6. Witzmann FA, Kim DH, Fitts RH. Hindlimb immobilization: length-tension and contractile properties of skeletal muscle. J Appl Physiol 1982b: 335–345.
7. Lundberg A, Svensson OK, Németh G, Selvik G. The axis of rotation of the ankle joint. J Bone Joint Surg 1989; 71-B: 94–99.
8. Dvir Z. Isokinetic muscle testing, interpretation and clinical applications. Singapore: Longman Publishers, 1995.
9. Williams M, Lissner HR. Biomechanics of human motion. Philadelphia: WB Saunders, 1962.
10. Heinonen A, Sievänen H, Viitasalo J, et al. Reproducibility of computer measurement of maximal isometric strength and electromyography in sedentary middle-aged women. Eur J Appl Physiol 1994; 68: 310–314.
11. Sepic SB, Murray MP, Mollinger LA, Spurr GB, Gardner GM. Strength and range of motion in the ankle in two age groups of men and women. Am J Phys Med 1986; 65: 75–84.

12. Schaik van CS, Hicks AL, McCartney N. An evaluation of the length-tension relationship in elderly human ankle dorsiflexors. J Gerontol 1994; 49: B121–B127.
13. Marsh E, Sale D, McComas AJ, Quinlan J. Influence of joint position on ankle dorsiflexion in humans. J Appl Physiol 1981; 51: 160–167.
14. Vander Linden DW, Kukulka CG, Söderberg GL. The effect of muscle length on motor unit discharge characteristics in human tibialis anterior muscle. Exp Brain Res 1991; 84: 210–218.
15. Booth FW. Physiologic and biochemical effects of immobilization on muscle. Clin Orthop Relat R 1987; 219: 15–20.
16. Dittmer DK, Teasell R. Complications of immobilization and bed rest. Can Fam Physician 1993; 39: 1428–1437.
17. Henriksson-Larsen KB, Lexell J, Sjostrom M. Distribution of different fibre types in human skeletal muscles. I. Method for the preparation and analysis of cross-sections of whole tibialis anterior. Histochem J 1983; 15: 167–178.
18. Jennekens FGI, Tomlinson BE, Walton JN. Data on the distribution of fibre types in five human limb muscles. J Neurol Sci 1971; 14: 245–257.
19. Tropp H, Norlin R. Ankle performance after ankle fracture: a randomized study of early mobilization. Foot Ankle 1995; 16: 79–83.
20. Gogia PP, Schneider VS, LeBlanc AD, Krebs J, Kasson C, Pientok C. Bed rest effect on extremity muscle torque in healthy men. Arch Phys Med Rehabil 1988; 69: 1030–1032.
21. Germain P, Güell A, Marini JF. Muscle strength during bedrest with and without muscle exercise as a countermeasure. Eur J Appl Physiol 1995; 71: 342–348.
22. Veldhuizen JW, Koene FMM, Oostvogel HJM, Thiel van TPH, Verstappen FTJ. The effects of a supportive knee brace on leg performance in healthy subjects. Int J Sports Med 1991; 12: 577–580.
23. Jaweed MM, Grana E, Monga TN, Mirabi B. Evaluation of neuromuscular function after 30 days of disuse. Proceedings PMR Congress 1996 Herzliya, Israel.
24. Rozier CK, Elder JD, Brown M. Prevention of atrophy by isometric exercise of a casted leg. J Sports Med 1979; 19: 191–194.
25. Fischer RD. The measured effect of taping, joint range of motion, and their interaction, upon the production of isometric ankle torques. Athletic Training 1982: 218–223.
26. McComas AJ. Human neuromuscular adaptations that accompany changes in activity. Med Sci Sports Exer 1994; 26: 1498–1509.
27. Savolainen J, Myllylä V, Myllylä R, Vihko V, Väänänen K, Takala TES. Effects of denervation and immobilization on collagen synthesis in rat skeletal muscle and tendon. Am J Physiol 1988; 254: 897–902.
28. Baker JH, Matsumoto DE. Adaptation of skeletal muscle to immobilization in a shortened position. Muscle & Nerve 1988; II: 231–244.
29. Nicks DK, Beneke WM, Key RM, Timson BF. Muscle fibre size and number following immobilisation atrophy. J Anat 1989; 163: 1–5.
30. Sargeant AJ, Davies CTM, Edwards RHT, Maunder C, Young A. Functional and structural changes after disuse of human muscle. Clin Sci Molec Med 1977; 52: 337–342.
31. White MJ, Davies CTM. The effects of immobilization, after lower leg fracture, on the contractile properties of human triceps surea. Clin Sci 1984; 66: 277–282.
32. Booth FW. Effect of limb immobilization on skeletal muscle. J Appl Physiol 1982; 52: 1113–1118.
33. Booth FW, Seider MJ. Recovery of skeletal muscle after 3 months of hindlimb immobilization in rats. J Appl Physiol 1979; 47: 435–439.
34. Witzmann FA, Kim DH, Fitts RH. Recovery time course in contractile function of fast and slow skeletal muscle after hindlimb immobilization. J Appl Physiol 1982; 52: 677–682.
35. Vandervoort AA, McComas AJ. Contractile changes in opposing muscles of the human ankle joint with aging. J Appl Physiol 1986; 61: 361–367.
36. Vandervoort AA, Chesworth BM, Cunningham DA, Patterson DH, Rechnitzer PA, Koval JJ. Age and sex effects on mobility of the human ankle. J Gerontol A Biol Sci Med Sci 1992; 47: M17–M21.
37. Hicks AL, McCartney N. Gender differences in isometric contractile properties and fatigability in elderly human muscle. Can J Appl Physiol 1996; 21: 441–454.
38. Thelen DG, Schultz AB, Alexander NB, Ashton-Miller JA. Effects of age on rapid ankle torque development. J Gerontol 1996; 51A: M226–M232.