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Luis M. Alegre[a]; Fernando Jiménez[a]; José Manuel Gonzalo-Orden[b]; Rafael Martín-Acero[c]; Xavier Aguado[a]

[a] Facultad de Ciencias del Deporte, Universidad de Castilla-La Mancha, Toledo [b] Departamento de Patología Animal (Medicina Animal), Universidad de León, León [c] INEF de Galicia, Universidad de Coruña, Coruña, Spain

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Effects of dynamic resistance training on fascicle length and isometric strength

LUIS M. ALEGRE[1], FERNANDO JIMÉNEZ[1], JOSÉ MANUEL GONZALO-ORDEN[2], RAFAEL MARTÍN-ACERO[3], & XAVIER AGUADO[1]

[1]*Facultad de Ciencias del Deporte, Universidad de Castilla-La Mancha, Toledo,* [2]*Departamento de Patología Animal (Medicina Animal), Universidad de León, León, and* [3]*INEF de Galicia, Universidad de Coruña, Coruña, Spain*

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Abstract

The aims of this study were to assess changes in muscle architecture, isometric and dynamic strength of the leg extensor muscles, resulting from dynamic resistance training, and the relationships between strength and muscle architecture variables. The participants ($n = 30$) were randomly assigned to one of two groups. The training group ($n = 16$; age 21.8 $\pm$ 2.3 years, body mass 74.8 $\pm$ 9.2 kg, height 1.75 $\pm$ 0.08 m) performed dynamic resistance training for 13 weeks. The control group ($n = 14$; age 19.9 $\pm$ 1.5 years, body mass 74.0 $\pm$ 8.5 kg, height 1.76 $\pm$ 0.05 m) did not perform any resistance training. Maximal dynamic and isometric strength were tested in both groups, before and after the training period. The members of the training group used the free-weight squat lift (90°) as their training exercise. The concentric phase of the squat was performed explosively. Skeletal muscle architecture of the vastus lateralis was visualized using ultrasonography. At the end of the study, significant increases in vastus lateralis muscle thickness (+6.9%, $P < 0.001$), fascicle length (+10.3%, $P < 0.05$), one-repetition maximum (+8.2%, $P < 0.05$), rate of force development (+23.8%, $P < 0.05$) and average force produced in the first 500 ms (+11.7%, $P < 0.05$) were seen only in the training group. Adaptations to the muscle architecture in the training group limited the loss of fibre force, and improved the capacity for developing higher velocities of contraction. The architectural changes in the training group were similar to those seen in studies where high-speed training was performed. In conclusion, dynamic resistance training with light loads leads to increases in muscle thickness and fascicle length, which might be related to a more efficient transmission of fibre force to the tendon.

Keywords: *Pennation, biomechanics, vastus lateralis, fascicle length, resistance training, isometric strength*

Introduction

The response of skeletal muscle to resistance training is commonly associated with an increase in muscle mass, neural adaptations and increases in force-generating capacity. A muscle's architecture has been reported to influence its contraction properties, because fibre length and pennation angle are closely associated with differences in muscle shortening velocity (Wickiewicz, Roy, Powell, Perrine, & Edgerton, 1984). Therefore, adaptations to different resistance training programmes might be modulated by the muscle architecture changes specific to each.

Several longitudinal studies have been conducted on the influence of resistance training on muscle architecture (Aagaard *et al.*, 2001; Blazevich, 2000; Blazevich, Gill, Brooks, & Newton, 2003; Blazevich & Giorgi, 2001; Kanehisa *et al.*, 2002; Kawakami, Abe, Kuno, & Fukunaga, 1995; Rutherford & Jones, 1992). It has been demonstrated that specific regimes of training or physical activity evoke changes in fibre pennation angle. The most common changes resulting from heavy resistance training are increases in muscle thickness, pennation angle and cross-sectional area (CSA) (Aagaard *et al.*, 2001; Blazevich & Giorgi, 2001; Kawakami *et al.*, 1995; Narici, 1999). However, other studies have reported no changes or even decreases in pennation angle after a period of resistance training (Blazevich & Giorgi, 2001; Blazevich *et al.*, 2003; Rutherford & Jones, 1992). These inconsistencies could have resulted from differences in training load and velocity-specific adaptations (Blazevich *et al.*, 2003).

It is unclear how lighter training loads than those used in previous studies could affect muscle architecture, and few studies have correlated muscle architecture with performance in sprint or strength tests (Abe, Fukashiro, Harada, & Kawamoto, 2001;

Correspondence: L. M. Alegre, Facultad de Ciencias del Deporte, Universidad de Castilla-La Mancha, Campus tecnológico, Avda. Carlos III, s/n, 45071 Toledo, Spain. E-mail: luis.alegre@uclm.es

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Abe, Kumagai, & Brechue, 2000; Brechue & Abe, 2002; Kumagai *et al.*, 2000). Recently, it has been reported that an isometric squat test can be used to predic one-repetition maximum performance. Nonetheless, the relationship between dynamic strength changes and isometric strength is not strong, but improves if the movement pattern is similar to the training task (Blazevich, Gill, & Newton, 2002).

The aims of this study were to examine changes in muscle architecture, isometric and dynamic strength of the leg extensor muscles, resulting from dynamic resistance training, and the relationships between strength and muscle architecture variables in a group of physical education students. It was hypothesized that there would be specific changes in muscle architecture after resistance training with light loads.

Methods

Thirty-six male physical education students volunteered to take part in the study. All of the participants were physically active, but none were specifically trained. The participants were randomly assigned to one of two groups, a training group and a control group. Six participants did not complete the study for various personal reasons, two from the training group and four from the control group, leaving 16 individuals (age 21.8 ± 2.3 years, body mass 74.8 ± 9.2 kg, height 1.75 ± 0.08 m, percent body fat 9.5 ± 2.45) in the training group and 14 individuals (age 19.9 ± 1.5 years, body mass 74.0 ± 8.5 kg, height 1.76 ± 0.05 m, percent body fat $9.7 \pm 3.0\%$) in the control group (see Table I). The members of the training group performed 33 sessions of dynamic resistance training over 13 weeks. The members of the control group did not perform any resistance training, but instead continued their normal activities for the duration of the experiment.

The members of the training group performed a 10-repetition maximum half squat test and an isometric test. Participants with no previous experience of resistance training could not express their maximal dynamic strength in a one-repetition-maximum (1-RM) test. One-repetition maximum performance was estimated by averaging the values obtained using the Brzycki and Epley equations (Brzycki, 1993; Epley, 1985) (see equations 1 and 2):

$$1 - \mathrm{RM}_{\mathrm{Brzycki}} = \mathrm{Load}(1.0278 - 0.0278 \cdot \mathrm{repetitions}) \quad (1)$$

$$1 - \mathrm{RM}_{\mathrm{Epley}} = (\mathrm{Load} \cdot 0.033 \cdot \mathrm{repetitions}) + \mathrm{Load} \quad (2)$$

where load is in kilograms.

For the isometric test, the participants were positioned in a squat rack with the knee at 90°. On command, they were instructed to exert a force as hard and as fast as possible and hold it for 4 s. The force produced during the squat was recorded by a force platform (Dinascan 600M, IBV, Spain), on which the participants were placed during each trial. One-repetition maximum performance, peak isometric force, maximal rate of force development and the average force produced in the first 500 ms (F500) were assessed in both groups, before and after the training period.

Anthropometry

Each participant's body composition was evaluated on the following parameters (Carter, 1982): body mass, height, fat-free mass (FFM) and percent body fat. Skinfold measurements were taken from six sites (triceps, subscapular, umbilicus, suprailium, thigh and lower leg) using Holtain callipers (Holtain, Croswell, Crymmych, UK). Fat-free mass was calculated by subtracting fat mass from total mass. Thigh length was measured from the greater trochanter to the lateral condyle of the femur. Thigh circumference was measured directly below the gluteal fold, and lower leg circumference was measured at the maximal circumference of the calf muscle.

Table I. Mean physical characteristics of the participants before and after the training period (standard deviation in parentheses).

	Pre-training		Post-training	
Variables	T group (N = 16)	C group (N = 14)	T group (N = 16)	C group (N = 14)
Body mass (Kg)	74.8 (9.2)	74.0 (8.5)	74.7 (8.8)	73.8 (8.6)
Height (cm)	175.1 (8.3)	176.1 (5.4)	175.0 (8.6)	176.3 (5.4)
FFM (kg)	67.6 (7.8)	66.6 (6.5)	67.5 (7.6)	66.7 (6.2)
% body fat	9.5 (2.4)	9.7 (3.0)	9.6 (2.5)	9.5 (2.5)
Thigh circumference (cm)	57.8 (3.8)	58.4 (3.2)	58.9 (3.5)^{b**}	57.0 (3.0)^{ae***}
Thigh length (cm)	44.7 (2.6)	44.6 (2.4)	44.5 (2.7)	44.6 (2.4)

[a]Control group pre-training vs. control group post-training, $P < 0.05$. [b]Training group pre-training vs. training group post-training, $P < 0.05$; b★★ = Training group pre-training vs. training group post-training, $P < 0.01$; e★★★ = significant time × group interaction, $P < 0.01$. ★ shows the level of statistical significance of the differences: no ★ = $P < 0.05$; ★★ = $P < 0.01$; ★★★ = $P < 0.001$, and this symbol is utilised in the three tables, therefore "b★★" means "training group pre-training vs. training group post training, $P < 0.01$.

Skeletal muscle architecture

B-mode ultrasonography was used to record sagittal images of the vastus lateralis while the participants lay supine with the knee fully extended. All participants remained relaxed during the ultrasound scanning. Ultrasound images were recorded using a Toshiba sonolayer Just Vision 400 real-time scanner (Toshiba, Tokyo, Japan) with a 7.5 MHz linear array transducer.

Isolated muscle thickness and fascicle pennation angle (midway between the greater trochanter and lateral condyle of the femur) were measured *in vivo* using the ultrasonograph.

The mediolateral width of the vastus lateralis was determined over the skin surface and the position of one-half of the width was used as the measurement site. The pennation angle was defined as the angle between the fascicle and deep aponeurosis (Figure 1). For the determination of fascicle pennation angle, the position of the transducer was manipulated while viewing the ultrasound image in real time. The angles between the echoes of the deep aponeurosis of the muscle and the echoes from interspaces among the fascicles were measured. The distance between the subcutaneous adipose tissue–muscle interface and intermuscular interface was defined as muscle thickness. Fascicle length was estimated as the length of the hypotenuse of a triangle with an angle equal to the pennation angle, and the side opposite to this angle equal to the muscle thickness, by the following equation:

$$\text{Fascicle length} = \text{Muscle thickness}/\sin(\text{pennation angle})$$

The model did not account for fascicle curvature.

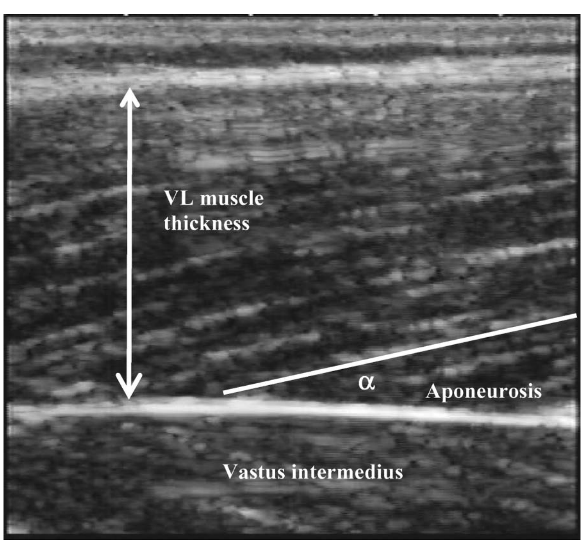

Figure 1. Sagittal ultrasound image of the vastus lateralis (VL). Vastus lateralis pennation angle (α) was measured between the deep aponeurosis (horizontal white line) and the fascicles (diagonal white lines). Muscle thickness was obtained by measuring the distance between the superficial and deep aponeuroses.

The ultrasound images from the vastus lateralis were recorded on videotape and subsequently analysed by the medical software Osiris v. 3.6 (University Hospital of Geneva, Switzerland). The examiner took five images from each recording and after accounting for the architecture variables, he excluded those which showed the longest and the shortest fascicle length. Then, means of muscle thickness, pennation angle and fascicle length were assessed from the three images left and used for further analysis. The coefficients of variation for repeated scanning (five different days) of muscle thickness, pennation angle and fascicle length measurements were 2.1, 5.2 and 5.5% respectively. With the same methodology, the intraclass correlation coefficients ranged from 0.95 ($P < 0.001$; fascicle length) to 0.996 ($P < 0.001$; muscle thickness and pennation angle).

Familiarization

Eight training sessions (training group) and five training sessions (control group) were conducted using light resistance before the testing to familiarize the participants with the equipment, training protocol and correct exercise technique. In addition, this familiarization period was designed to control strength increases resulting from motor learning and to avoid injuries.

Training

The members of the training group participated in resistance training 3 days a week for 13 weeks. Each session was supervised by a qualified trainer. Adherence rate was monitored and participants who did not attend a minimum of 90% of the training sessions were excluded from the study. The resistance training exercise was the half squat lift. The participants performed three to four sets of 6–12 repetitions with a 3 min rest between sets. During the first 2 weeks, the participants trained at an intensity of 30% of 1-RM and were instructed to complete three sets of 12 repetitions with a 3 min rest between sets. Training intensity during weeks 3 to 13 was 50–60% of 1-RM. Training intensity was progressively increased until week 9, and training volume was reduced throughout the training period by reducing the number of repetitions per set from 12 to 6–8. Each session began with a 5 min warm-up on either a bicycle ergometer or a treadmill at a low intensity, followed by static stretching of the agonist and antagonist muscles. Then, the participants performed two sets of 8 repetitions with a load equal to 50% of the daily training load to complete the warm-up. The concentric phase of each repetition was performed explosively, but the participants were not allowed to jump, because this might have produced forced stretching in the fascicles of the vastus lateralis. The eccentric phase lasted approximately 1 s. Progression was evaluated by testing maximal dynamic strength half way through the training period.

Statistical analysis

The results are expressed as means ± standard deviation. A 2 × 2 factorial analysis of variance (ANOVA) was used to test for differences in time (pre – post) and group (training and control) for all the measured variables. The Scheffé procedure was used for *post hoc* analysis where necessary. Relationships between selected variables were examined using Pearson product – moment correlations. Statistical significance was set at $P < 0.05$.

Results

After training, statistically significant increases in 1-RM, rate of force development and the average force produced in the first 500 ms were observed only in the training group. The increases in absolute and relative peak isometric force in the training group were not significant. Nonetheless, these variables decreased in the control group (Table II). After training, absolute and relative fascicle length increased in the training group by 10.3% and 10.5% ($P < 0.05$) respectively, and thickness of the vastus lateralis increased by 6.9% ($P < 0.001$) (Table III). There were no significant changes in muscle architecture for the control group in the second test. There was a significant time × group interaction for thigh circumference, which increased in the training group but decreased in the control group ($F_{1,28} = 18.81$; $P < 0.001$). There were also significant interactions for 1-RM performance ($F_{1,28} = 9.90$; $P < 0.01$) and rate of force development ($F_{1,28} = 5.61$; $P < 0.05$), which increased in the training group and decreased in the control group (Table II). Finally, the ANOVA also showed a significant time × group interaction for thickness of the vastus lateralis ($F_{1,28} = 12.87$; $P < 0.01$). After the resistance training, muscle thickness increased in the training group but was unchanged in the control group. There was a slight positive correlation between 1-RM and thickness of the vastus lateralis

Table II. Mean pre- and post-training strength variables in the two groups (standard deviation in parentheses).

	Pre-training		Post-training	
Variables	T group (N = 16)	C group (N = 14)	T group (N = 16)	C group (N = 14)
1 RM squat (kg)	158 (32)	152 (21)	171 (29)[ab★★]	147 (21)[e★★]
Peak isometric force (N)	1593 (359)	1450 (233)	1669 (297)[a]	1419 (207)
Peak isometric force/ Body weight (BW)	2.20 (0.57)	2.01 (0.28)	2.30 (0.47)[a]	1.96 (0.24)
Maximal rate of force development (N/s)	7608 (2638)	8822 (4032)	9416 (2711)[b★★]	8116 (2374)[e]
Force produced in the first 500 ms (N)	1197 (362)	1141 (224)	1337 (285)[b]	1155 (210)

[a]Training group vs. control group post-training, $P < 0.05$. [b]Training group pre-training vs. training group post-training, $P < 0.05$. [c]Training group pre-training vs. training group post-training, $P < 0.01$. [d]Significant time × group interaction, $P < 0.05$. [e]Significant time × group interaction, $P < 0.01$.
We have utilised "e" in the three tables to show significant interactions, so "c" and "d" are not used in table 2. The correct explanation of the symbols in the Table 2 is as follows: a = Training group vs. conrol group post-training, $P < 0.05$; b = Training group pre-training vs. training group post-training, $P < 0.05$; b★★ = $P < 0.01$; e = Significant time × group interaction, $P < 0.05$, e★★ = $P < 0.01$.

Table III. Mean pre- and post-training muscle architecture variables in the two groups (standard deviation in parentheses).

	Pre-training		Post-training	
Variables	T group (N = 16)	C group (N = 14)	T group (N = 16)	C group (N = 14)
VL muscle thickness (cm)	2.30 (0.42)	2.23 (0.32)	2.46 (0.36)[a★★★]	2.21 (0.35)[e★★]
VL pennation angle (°)	16.2 (3.2)	15.9 (1.9)	15.8 (2.8)	15.3 (2.4)
VL fascicle length (cm)	8.38 (1.43)	8.22 (1.17)	9.24 (1.53)[a]	8.47 (1.14)
VL fascicle length/limb length	0.19 (0.04)	0.18 (0.03)	0.21 (0.03)[a]	0.19 (0.02)

[a]Training group pre-training vs. training group post-training, $P < 0.05$. [b]Training group pre-training vs. training group post-training, $P < 0.001$. [c]Significant time × group interaction, $P < 0.01$. VL = vastus lateralis.
"b" is not utilised in table 3, only "a", "a★★★" and "e★★". The correct explanation of the symbols in the Table 3 is as follows: a = Training group pre-training vs. training group post-training, $P < 0.05$; a★★★ = $P < 0.001$; e★★ = Significant time × group interaction, $P < 0.01$.

in the training group (pre-training: $r = 0.52$; post-training: $r = 0.54$; $P < 0.05$). After training, significant positive correlations were observed in the training group between vastus lateralis pennation angle and peak isometric force ($r = 0.57$, $P < 0.05$), relative peak isometric force ($r = 0.56$, $P < 0.05$), rate of force development ($r = 0.55$, $P < 0.05$) and the average force produced in the first 500 ms ($r = 0.80$, $P < 0.001$).

Discussion

The participants in the training group were able to increase their 1-RM after 13 weeks of training, even with the relative light training load. These strength gains were accompanied by considerable and significant increases in the rate of force development and the average force produced in the first 500 ms, so that the training group also increased its explosive isometric strength. The changes in the rate of force development and the average force produced in the first 500 ms in the training group were similar in magnitude to those observed in the study of Young and Bilby (1993) (Table IV). The resistance training intervention in the experiment also led to some increases in relative and absolute isometric strength, but these changes were not significant. In general, the magnitude of the strength gains observed in the current study was below the range reported for heavy resistance training (Table IV). The explanation for these discrepancies could be related to the relatively modest total training load performed by the participants in this study. For example, the participants in the study of Häkkinen *et al.* (2003) performed only 20% of their training volume with similar intensities to that in our study. The rates of force development were similar to those in the studies of Häkkinen, Izquierdo, Aguado, Newton and Kraemer (1996) and Izquierdo *et al.* (1998, 1999) involving physical education students. In these studies, the protocols were identical to ours.

The fascicle lengths, pennation angles and muscle thicknesses of our participants were within the ranges reported in the literature for similar populations (Abe *et al.*, 2000; Alegre, Aznar, Delgado, Jiménez, & Aguado, 2003; Kearns, Abe, & Brechue, 2000; Kumagai *et al.*, 2000), especially when limb lengths are taken into account. Previous studies have reported that limb dimensions and muscle architecture variables are related (Aagaard *et al.*, 2001; Kanehisa, Muraoka, Kawakami, & Fukunaga, 2003), so taller individuals tend to have longer fascicles and smaller pennation angles. In fact, after training, there was a negative correlation between height and vastus lateralis pennation angle.

The results of the present study show an increase in thickness of the vastus lateralis, and a slight decrease in pennation angle, in response to explosive resistance training. This leads to an increase in fascicle length, which would limit the loss of fibre force, and a better capacity for developing higher velocities of contraction (Kumagai *et al.*, 2000). The significant time × group interaction for thickness of the vastus lateralis would indicate that the changes were dependent on the resistance training performed by the members of the training group.

Changes in thickness of the vastus lateralis for the training group were less than those described by Kawakami *et al.* (1995), Blazevich and Giorgi (2001) and Aagaard *et al.* (2001), who reported increases of 27%, 29.5% and 10.2% (quadriceps cross-sectional area) respectively. Nonetheless, our increases were greater than those described by Rutherford and Jones (1992), who reported an increase of 4.7% in vastus lateralis cross-sectional area after 12 weeks of strength training. Typical resistance training adaptations are

Table IV. Post-training changes in the knee extensor muscles in the present study and previous research.

Study	N	Population	Training period (weeks)	Intensity	1 RM (percent increase)	Relative Isometric force (percent increase)	Absolute Isometric force (percent increase)	RFD (percent increase)
Present study	16	male physical education students	13	30 – 60% of 1 RM	8.2	4.5	4.8	23.8
Young and Bilby (1993)	18	male college students	7.5	8 – 12 RM	21.0 – 22.5	10.7 – 22.7	12.6 – 24.6	23.5 – 68.7
Baker *et al.* (1994)	33	male weight trainers	12	6 RM	24.3 – 25.3	–	–	–
Aagaard *et al.* (2001)	11	healthy men	14	3 – 12 RM	–	–	16	–
Häkkinen *et al.* (2003)	32	healthy men	21	50 – 80% of 1 RM	21 – 22	18 – 22	21 – 22	?

Note: RFD = rate of force development.

greater muscle thickness and pennation angles (Aagaard *et al.*, 2001; Kanehisa *et al.*, 2002; Kawakami *et al.*, 1995). However, training in the current study consisted of high-velocity contractions with light loads (< 60% of 1-RM), so the changes in muscle architecture could be similar to those in studies where high-speed training was performed (Blazevich *et al.*, 2003), with increases in muscle thickness (6.9%, $P < 0.001$) and fascicle length (10.3%, $P < 0.05$) being observed in the training group.

The changes in fascicle length in the training group were less marked than those in the study by Blazevich *et al.* (2003), who reported an increase of 24.9% in a group who performed sprint-jump training for 5 weeks. These differences may be attributed to the type of training performed by our experimental group, because jump squats were not allowed, to avoid the effect of forced stretching on fascicle lengthening. The concentric phase of training exercise was performed explosively, whereas the eccentric phase lasted 1 s. This suggests that explosive concentric contractions without forced stretching could lead to similar changes in muscle architecture as typical sprint-jump training, but of smaller magnitude. The factors responsible for fascicle lengthening in the training group might be specific adaptations of muscle architecture in response to explosive resistance training with light loads and/or the mechanical stimulus over the vastus lateralis during the eccentric phase of the training protocol. Fascicle lengthening in humans as a result of a mechanical stimulus is only speculative, but it has been observed in animal muscles (Lynn, Talbot, & Morgan, 1998). None of our participants had a background of regular strength training, so it is possible that the stimulus provided by the training exercise, with a significant increase in the working range of motion, would have changed the length–force curve of the vastus lateralis. Although in the present study sarcomere length was not measured, a theoretical implication of our findings is that sarcomeres from longer fascicles would work at their optimal length (Figure 2), whereas in a muscle with shorter fascicles the sarcomeres would work on the descending limb of their length–tension curve. The muscle architecture of the training group adapted to produce higher velocity contractions, with significant increases in muscle thickness and fascicle length.

The combination of greater muscle thickness and longer fascicles of the vastus lateralis after training would lead to greater force output at an identical shortening velocity (Kumagai *et al.*, 2000). The decrease in pennation angle would also improve force transmission through the fibres.

There were no significant correlations between muscle thickness and pennation angle, as in the study

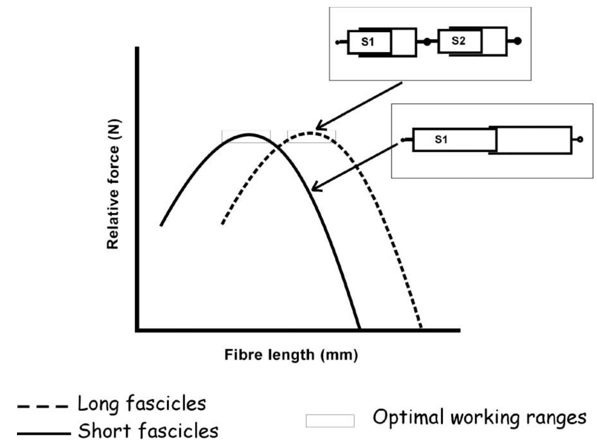

Figure 2. Schematic representation of two muscles with different fibre lengths. In the muscle with longer fibres the sarcomeres will be at their optimal length, whereas in the muscle with shorter fibres, with the same pre-stretching, the sarcomeres will be on the descending limb of the length–tension curve. S = sarcomere.

of Kearns *et al.* (2000). However, significant correlations between muscle size and fibre angulation have been reported previously (Aagaard *et al.*, 2001; Kawakami, Abe, & Fukunaga, 1993; Kawakami *et al.*, 1995). The relationship between these variables seems to change depending on the muscles and populations analysed. The strongest relationships have been found in the triceps brachii muscle, and in large and heterogeneous sample sizes (Ichinose, Kanehisa, Ito, Kawakami, & Fukunaga, 1998; Kawakami *et al.*, 1993, 2000). It remains unclear whether the two variables are related or not, and it might be different depending on the individual behaviour of each muscle. In the training group, there was a slightly positive correlation between muscle thickness and fascicle length ($r = 0.50$, $P < 0.05$). This relationship has been reported previously, but is usually associated with extreme muscle sizes (Brechue & Abe, 2002; Kearns *et al.*, 2000).

The training stimulus could have affected the relationships between pennation angle and the strength variables, possibly because in the training group the force transmission from the fascicles to the tendon of the knee extensor muscles was more efficient after training. After training, significant positive correlations were observed in the training group between vastus lateralis pennation angle and peak isometric force, relative peak isometric force, rate of force development and the average force produced in the first 500 ms. Pennation angle has been associated previously with muscle size (Aagaard *et al.*, 2001; Ichinose *et al.*, 1998; Kawakami *et al.*, 1993, 1995). Before training in our study, there was a non-significant correlation between muscle thickness and vastus lateralis pennation angle ($r = 0.48$), which became statistically significant after the training period ($r = 0.50$, $P < 0.05$).

Muscle size is closely associated with maximal voluntary strength, although there is a neural component in the expression of strength. This might be one of the reasons for the lack of correlations between muscle thickness and strength in our training group. However, post-training increases in the correlations between pennation angle and the strength variables might be related to an improvement in the utilization of muscle mass.

In conclusion, dynamic resistance training with light loads increases muscle thickness and fascicle length, which might be related to a more efficient transmission of fibre force to the tendon.

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References

Aagaard, P., Andersen, J. L., Dyhre-Poulsen, P., Leffers, A. M., Wagner, A., Magnusson, S. P. *et al.* (2001). A mechanism for increased contractile strength of human pennate muscle in response to strength training: Changes in muscle architecture. *Journal of Physiology*, *15*, 613–623.

Abe, T., Fukashiro, S., Harada, Y., & Kawamoto, K. (2001). Relationship between sprint performance and muscle fascicle length in female sprinters. *Journal of Physiological Anthropology and Applied Human Science*, *20*, 141–147.

Abe, T., Kumagai, K., & Brechue, W. F. (2000). Fascicle length of leg muscles is greater in sprinters than distance runners. *Medicine and Science in Sports and Exercise*, *32*, 1125–1129.

Alegre, L. M., Aznar, D., Delgado, T., Jiménez, F., & Aguado, X. (2003). Fuerza y arquitectura muscular en un grupo de estudiantes. *Revista de Entrenamiento Deportivo*, *17*, 23–29.

Baker, D., Wilson, G., & Carlyon, R. (1994). Periodization: The effect on strength of manipulating volume and intensity. *Journal of Strength and Conditioning Research*, *8*, 235–242.

Blazevich, A. J. (2001). Effect of movement pattern and velocity of strength training exercises on training adaptations during concurrent resistance and sprint/jump training. Doctoral dissertation, Southern Cross University, Lismore, NSW.

Blazevich, A. J., Gill, N. D., Bronks, R., & Newton, R. U. (2003). Training-specific muscle architecture adaptation after 5-wk training in athletes. *Medicine and Science in Sports and Exercise*, *35*, 2013–2022.

Blazevich, A. J., Gill, N., & Newton, R. U. (2002). Reliability and validity of two isometric squat tests. *Journal of Strength and Conditioning Research*, *16*, 298–304.

Blazevich, A. J., & Giorgi, A. (2001). Effect of testosterone administration and weight training on muscle architecture. *Medicine and Science in Sports and Exercise*, *33*, 1688–1693.

Brechue, W. F., & Abe, T. (2002). The role of FFM accumulation and skeletal muscle architecture in powerlifting performance. *European Journal of Applied Physiology*, *86*, 327–336.

Brzycki, M. (1993). Strength testing–predicting a one-rep max from reps-to-fatigue. *Journal of Physical Education, Recreation and Dance*, *64*, 88–90.

Carter, J. E. L. (1982). Anthropometric instruments and measurements used in the Montreal Olympic Games Anthropological Project. In J. E. L. Carter (Ed.), *Physical structure of Olympic athletes. Part I: Medicine and sport science* (Vol. 16, pp. 150–155). Basel: Karger.

Epley, B. (1985). *Poundage chart.* Lincoln, NE: Boyd Epley Workout.

Häkkinen, K., Alen, M., Kraemer, W. J., Gorostiaga, E., Izquierdo, M., Rusko, H. *et al.* (2003). Neuromuscular adaptations during concurrent strength and endurance training versus strength training. *European Journal of Applied Physiology*, *89*, 42–52.

Häkkinen, K., Izquierdo, M., Aguado, X., Newton, R. U., & Kraemer, W. J. (1996). Isometric and dynamic explosive force production of leg extensor muscles in men at different ages. *Journal of Human Movement Studies*, *31*, 105–121.

Ichinose, Y., Kanehisa, H., Ito, M., Kawakami, Y., & Fukunaga T. (1998). Morphological and functional differences in the elbow extensor muscle between highly trained male and female athletes. *European Journal of Applied Physiology*, *78*, 109–114.

Izquierdo, M., Aguado, X., Gonzalez, R., Lopez, J. L., & Häkkinen, K. (1999). Maximal and explosive force production capacity and balance performance in men of different ages. *European Journal of Applied Physiology*, *79*, 260–267.

Izquierdo, M., Aguado, X., Ribas, T., Linares, F., Vila, L., Voces, J. A. *et al.* (1998). Jumping performance, isometric force and muscle characteristics in non athletic young men. *Journal of Human Movement Studies*, *35*, 101–117.

Kanehisa, H., Muraoka, Y., Kawakami, Y., & Fukunaga, T. (2003). Fascicle arrangements of vastus lateralis and gastrocnemius muscles in highly trained soccer players and swimmers of both gender. *International Journal of Sports Medicine*, *24*, 90–95.

Kanehisa, H., Nagareda, H., Kawakami, Y., Akima, H., Masani, K., Kouzaki, M. *et al.* (2002). Effects of equivolume isometric training programs comprising medium or high resistance on muscle size and strength. *European Journal of Applied Physiology*, *87*, 112–119.

Kawakami, Y., Abe, T., & Fukunaga, T. (1993). Muscle-fiber pennation angles are greater in hypertrophied than in normal muscles. *Journal of Applied Physiology*, *74*, 2740–2744.

Kawakami, Y., Abe, T., Kuno, S., & Fukunaga, T. (1995). Training-induced changes in muscle architecture and specific tension. *European Journal of Applied Physiology*, *72*, 37–43.

Kawakami, Y., Ichinose, Y., Kubo, K., Ito, M., Imai, M., & Fukunaga, T. (2000). Architecture of contracting human muscles and its functional significance. *Journal of Applied Biomechanics*, *16*, 88–97.

Kearns, C. F., Abe, T., & Brechue, W. F. (2000). Muscle enlargement in sumo wrestlers includes increased muscle fascicle length. *European Journal of Applied Physiology*, *83*, 289–296.

Kumagai, K., Abe, T., & Brechue, W. F., Ryushi, T., Takano, S., & Mizuno, M. (2000). Sprint performance is related to muscle fascicle length in male 100-m sprinters. *Journal of Applied Physiology*, *88*, 811–816.

Lynn, R., Talbot, J. A., & Morgan, D. L. (1998). Differences in rat skeletal muscles after incline and decline running. *Journal of Applied Physiology*, *85*, 98–104.

Narici, M. (1999). Human skeletal muscle architecture studied *in vivo* by non-invasive imaging techniques: Functional significance and applications. *Journal of Electromyography and Kinesiology*, *9*, 97–103.

Rutherford, O. M., & Jones, D. A. (1992). Measurement of fibre pennation using ultrasound in the human quadriceps *in vivo*. *European Journal of Applied Physiology*, *65*, 433–437.

Wickiewicz, T. L., Roy, R. R., Powell, P. L., Perrine, J. J., & Edgerton, V. R. (1984). Muscle architecture and force–velocity relationships in humans. *Journal of Applied Physiology*, *57*, 435–443.

Young, W. B., & Bilby, G. E. (1993). The effect of voluntary effort to influence speed of contraction on strength, muscular power, and hypertrophy development. *Journal of Strength and Conditioning Research*, *7*, 172–178.