IMPACT OF RANGE OF MOTION DURING ECOLOGICALLY VALID RESISTANCE TRAINING PROTOCOLS ON MUSCLE SIZE, SUBCUTANEOUS FAT, AND STRENGTH

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ABSTRACT

McMahon, GE, Morse, CI, Burden, A, Winwood, K, and Onambéle, GL. Impact of range of motion during ecologically valid resistance training protocols on muscle size, subcutaneous fat, and strength. J Strength Cond Res 28(1): 245–255, 2014—The impact of using different resistance training (RT) kinematics, which therefore alters RT mechanics, and their subsequent effect on adaptations remain largely unreported. The aim of this study was to identify the differences to training at a longer (LR) compared with a shorter (SR) range of motion (ROM) and the time course of any changes during detraining. Recreationally active participants in LR (aged 19 ± 2.6 years; n = 8) and SR (aged 19 ± 3.4 years; n = 8) groups undertook 8 weeks of RT and 4 weeks of detraining. Muscle size, architecture, subcutaneous fat, and strength were measured at weeks 0, 8, 10, and 12 (repeated measures). A control group (aged 23 ± 2.4 years; n = 10) was also monitored during this period. Significant (p > 0.05) posttraining differences existed in strength (on average 4 ± 2 vs. 18 ± 2%), distal anatomical cross-sectional area (59 ± 15 vs. 16 ± 10%), fascicle length (23 ± 5 vs. 10 ± 2%), and subcutaneous fat (22 ± 8 vs. 5 ± 2%), with LR exhibiting greater adaptations than SR. Detraining resulted in significant (p > 0.05) deteriorations in all muscle parameters measured in both groups, with the SR group experiencing a more rapid relative loss of postexercise increases in strength than that experienced by the LR group (p > 0.05). Greater morphological and architectural RT adaptations in the LR (owing to higher mechanical stress) result in a more significant increase in strength compared with that of the SR. The practical implications for this body of work follow that LR should be observed in RT where increased muscle strength and size are the objective, because we demonstrate here that ROM should not be compromised for greater external loading.

KEY WORDS detraining, hypertrophy, muscle architecture, range of motion, stress, strength training

INTRODUCTION

To the strength and conditioning practitioner, the design of a resistance training (RT) program will incorporate a selection of exercises that will ideally reflect both functional tasks of a chosen sport and also the ability of the exercise to bring about a desired set of adaptations to enhance function and ideally, therefore, physical performance. Because muscle force is proportional to muscle cross-sectional area (29), is intimately linked with power, and is a key determinant to success in many sports, muscular hypertrophy is often a key outcome after RT. The degree of hypertrophy arises from the manipulation of the training stimulus: exercise selection and order, mode of contraction, intensity, recovery, and volume (38). Although studies on several of these variables are numerous, effects of training kinematics on training mechanics remain largely unreported. Taking the squat exercise (which is an exercise often used to overload the knee extensor muscle group during a hypertrophic training phase) as an example, studies have investigated the relationship between range of motion (ROM) of the squat and its effects on thigh muscle activation and joint moments (51), tibiofemoral shear and compressive forces (36), and on peak velocity and force (10). One potential important aspect of training kinematics (i.e., ROM) that practitioners may not have previously taken into consideration is the effects of ROM on muscle mechanics during RT, and the subsequent adaptations as a result. Suboptimal or inadequate loading of the muscle group therefore could lead to the goals of the RT program not being met.

As muscle length changes during force production to bring about movement, the moment arm of the series elastic component (i.e., the tendon) also changes. Therefore, the internal tension a muscle experiences at different joint angles will change despite there being no alterations in external
absolute load. Simultaneous to the change in moment arm is the effect of changing muscle length on actin-myosin interactions and thus crossbridge states (18). A changing muscle length will vary both these cellular factors, thus impacting on the force-length relationship in the muscle (37). The magnitude of mechanical stress is known to induce muscle hypertrophy (30); therefore, increased mechanical stress at 1 joint angle compared with another could act as a signal for additional sarcomerogenesis at that muscle length based on the differential stress imposed through the moment arm changes. To further augment sarcomerogenesis at different muscle lengths are the effects stretch has on muscle. Muscles undergoing different amounts of stretching and shortening have been shown to adapt to their new functional lengths by the addition or removal of sarcomeres in series (12, 46, 50), with an increase in functional length associated with increased protein synthesis (13).

This identifies “average muscle length-specific training” as a potential modulator of the training-induced hypertrophic response. Only 1 previous study to our knowledge (26) has investigated training at different joint angles on muscle size and function in vivo, but the results do not reflect what the theory would have predicted. Nine men completed a 12-week unilateral isometric training program (70% maximum voluntary contraction × 15 seconds × 6 sets) on the knee extensors at either a short (50° of knee flexion) or a long (100°) muscle length. The authors found that whole quadriceps volume increased significantly in both short (+10 ± 1%) and long (+11 ± 2%) muscle lengths, although there was no significant difference between the groups. However, it should be noted that the isometric-only protocol adopted by Kubo et al. (25) may not reflect the practices of individuals training to optimize gains in strength and hypertrophy in addition to the limited transfer of the functional aspect of an isometric exercise.

Architectural adaptations have also been shown to occur with RT. Alterations to the fascicle angle of pennation impacts on the physiological cross-sectional area (CSA) and therefore force-generating capacity (1) of muscle, whereas changes to fascicle length are associated with alterations to the force-velocity relationship (48), which therefore impacts potential power output. Regarding fascicle angle, there appears to be a strong relationship between increases in muscle size and increases in pennation angle (4, 19, 20). Although an increase in pennation angle is expected to allow an increase muscle force (up to an upper limit of 45°), at greater pennation angles, the effective contractile force exerted on the aponeurosis is reduced to a greater extent, off-setting the increase in force production from the increased number of actomyosin crossbridges activated in parallel (35, 42). Hence, it is important to monitor both fascicle angle and functional changes in strength in the muscle of interest. To systematically determine what changes are evident in the muscle in terms of hypertrophic and architectural changes is therefore key to optimizing training protocols with the associated training adaptations.

It is also important to describe how the muscle responds to a reduction in loading. Detraining is the partial or complete loss of training-induced adaptations, in response to an insufficient loading stimulus (32). Significant decrements in strength, electromyography (EMG), and mean fiber CSA have been reported in as little as 2 weeks of detraining (16), with similar observations in chronic detraining periods (≥4 weeks) alluding to either losses in mass, strength or neural activation, or combinations of these factors (15, 25, 34). Also, most studies have tended to report changes after detraining after similar time courses to the preceding RT, that is, between 3 and 6 months. If there appears to be a greater hypertrophic response at 1 muscle length over another, it would also be of interest to determine whether there is a differential modulation of detraining-induced mal-adaptations after greater initial gains from RT at different muscle lengths. Thus, if these greater gains are still evident after detraining, it would further highlight the value of using more optimal training mechanics within an RT program.

The purpose of this study was to therefore describe the changes to vastus lateralis (VL) anatomical CSA (aCSA), architecture, subcutaneous fat content, and strength after 8 weeks of dynamic resistance exercise at 50° compared with 90° of knee flexion, using an ecologically valid training regime. In brief, the specified angle is the position at which the training load is held isometrically for 2 seconds. With 50°, this involves a shorter ROM (SR) in the dynamic phase of the exercise and thus a shorter “average muscle length,” whereas with 90°, this involves a longer ROM (LR) in the dynamic phase of the exercise and thus a longer “average muscle length.” A second objective was to describe the effects of the detraining time course over 4 weeks on the aforementioned variables. It was hypothesized that the group training at longer muscle length (90° joint angle) would undergo a greater amount of skeletal muscle hypertrophy because of increased physiological stress and stretch on sarcomeres compared with the group training at 50°. It was also expected that the LR group would continue to have a large muscle mass after detraining, because of greater initial gains. Strength-related parameters were expected to follow the same pattern as those associated with hypertrophy.

**METHODS**
**Experimental Approach to the Problem**

We sought to compare changes in muscle size, architecture, function, and subcutaneous fat after 8 weeks of RT and 4 weeks of detraining covering 2 distinctly different ROMs (the between-subjects independent variable) to identify the most effective method of RT based on the adaptations observed (dependent variables described below). The participants performed isoinertial RT at either a shorter average muscle length (ROM 0–50° knee flexion) or a longer average muscle length (ROM 0–90° knee flexion) 3 times per week at 80% RM during the training period and performed habitual activity during detraining. Dependent variables were
measured at baseline, posttraining, after 2 weeks of detraining and again after a further 2 weeks of detraining (the within-subject independent variable). Testing was completed within 3 hours of the time of day at weeks 0, 8, 10, and 12 to minimize any impact of diurnal variability in muscle function (28). The participants were allowed to drink water ad libitum during testing and training sessions.

Subjects
Twenty-six volunteers (14 men and 12 women; age range of 18 to 26 years old) from the local university campus gave written informed consent to participate in this study with all procedures and experimental protocols approved by the local Ethics Committee within the Department of Exercise and Sport Science. Exclusion criteria included the presence of any known musculoskeletal, neurological, and inflammatory and metabolic disorders or injury. The participants took part in recreational activities such as team sports and had either never taken part in lower limb RT or over the last 12 months. Sixteen activity-matched men and women were randomly assigned to either the SR (n = 8–4 men, 4 women) training group or to the long ROM (LR; n = 8–4 men, 4 women) training group. Ten participants (6 men and 4 women) were assigned to the nontraining control group (Con) to monitor for random variation in the muscle parameters investigated in this population over the training and detraining periods. The physical characteristics of the study population are outlined in Table 1. A 1-way analysis of variance (ANOVA) revealed that the population was homogeneous at baseline for all parameters of interest and in physical characteristics (p > 0.05). As body mass and external load provide the total training stimulus in a number of the leg exercises adopted in the training program (2 out of the 6), it should be noted that the participant groups showed no difference in body mass at baseline, week 8, 10, or 12. Furthermore, it was felt that training at loads relative to 1RM provided greater external validity to the practices of individuals undertaking RT.

Procedures
Resistance Training Program. Resistance training was performed 3 times per week (twice supervised and 1 home-based session) by both the SR and LR training groups for 8 weeks, using a combination of free, machine (Pulse Fitness, Congleton, United Kingdom) and body weights. A generalized warm-up was completed at 70–75% age-predicted maximum heart rate on a treadmill for 5 minutes, after which a goniometer was attached to the center of rotation of the knee. As the subject performed each exercise (Table 2), the goniometer rotated from 0° (full extension), and a training partner confirmed from the scale when the participant had reached 50 or 90° of knee flexion during the eccentric phase and therefore could hold the load steady over 2 seconds, before beginning the concentric phase of movement. Movement speed was dictated by a 1-second metronome. All exercises involved eccentric and concentric loading, except for the Sampson chair, which was isometric loading. The subjects completed 2 familiarization sessions at 70% of 1RM before commencing the RT program. Exercises were performed at 80% of the 1RM as determined at the training angle, for example, the SR group 1RM was the greatest weight lifted whilst performing at 50° knee flexion. The 1RM values were measured every 2 weeks, and the training loads were adjusted accordingly. Manipulation of the exercise variables (exercise selection and order, repetitions, sets, recovery, and intensity shown in Table 2) were all chosen based on empirical evidence presented in the American College of Sports Medicine’s Progression Models for RT for Healthy Adults for increasing muscle hypertrophy (38).

Muscle Architecture and Subcutaneous Fat. Architecture was measured at rest with each participant seated in an upright position on an isokinetic dynamometer (Cybex, Phoenix Healthcare Products, Nottingham, United Kingdom). After calibration, each participant was positioned with a hip angle of 80° (straight back 90°) and knee at 90° knee flexion (straight leg 0°). All muscle architectural measurements were determined using real-time ultrasonography (AU5, Esaote Biomedica, Genoa, Italy) at rest, with images captured at 25 Hz using a digital video recorder (Tevion, Medion Australia Pty Ltd, St Leonards, Australia). Vastus Lateralis fascicle pennation angle (θ) was measured as the angle of fascicle insertion into the deep aponeurosis (42). Images were obtained perpendicular to the dermal surface of the VL and oriented along the midsagittal plane of the muscle. Images were taken at 25, 50, and 75% of the total femur length (as described below) and 50% of muscle width at each point (where 50% muscle width is defined as the midpoint between the fascia separating the VL and rectus femoris, and fascia separating the VL and biceps femoris muscles). Fascicle length was defined as the length of the fascicular path between the deep aponeurosis and superficial aponeurosis of the VL. The majority of fascicles extended off the acquired image, where the missing portion was estimated by linear extrapolation. This was achieved by measuring the linear distance from the identifiable end of a fascicle to the intersection of a line drawn from the fascicle and a line drawn from the superficial aponeurosis. This method has

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (y)</th>
<th>Mass (kg)</th>
<th>Height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR</td>
<td>19 ± 3.4</td>
<td>74.9 ± 10.1</td>
<td>174 ± 13.3</td>
</tr>
<tr>
<td>LR</td>
<td>19 ± 2.6</td>
<td>73.8 ± 14.9</td>
<td>171 ± 11.8</td>
</tr>
<tr>
<td>Con</td>
<td>23 ± 2.4</td>
<td>77.9 ± 13.1</td>
<td>176 ± 9.5</td>
</tr>
</tbody>
</table>

*SR = shorter range of motion; LR = longer range of motion; Con = control group.
been shown to produce reliable results previously (4). All images were analyzed and measured using Image J (Wayne Rasband, National Institutes of Health, Bethesda, MD, USA).

Subcutaneous fat was estimated using the same images as taken for muscle architecture. After calibration in Image J to coincide with the scale of the ultrasound image, a line from the top to the bottom of the layer of fat visualized was drawn at 3 regular intervals on the ultrasound image. The average lengths of these 3 lines were taken to estimate the average thickness of the subcutaneous fat layer in millimeters. Care was taken not to deform or compress the subcutaneous fat with minimal pressure applied to the dermal surface with the ultrasound probe.

**Muscle Force Modeling.** Because of the changing moment arm length of the patella tendon at discrete knee joint angles, differences in muscle force produced between the groups had to be accounted for. Thus, quadriceps forces at the patella tendon were calculated as follows:

\[
\text{QuadForce} = \frac{\left(\text{QuadMaxTorque} + \text{HamCoTorque}\right)}{\text{Moment Arm}_{PT}}
\]

(1)

where

\[
\text{HamCoTorque} = \frac{(\text{Co} - \text{ConEMG} \times \text{FlexMaxTorque})}{(\text{Max BF}_{\text{EMG}})}
\]

(2)

where Co-ConEMG is co-contraction of the antagonist muscle (biceps femoris), and Max BF_{EMG} is the maximum antagonist EMG. The Flex\text{MaxTorque} is maximum flexion torque and Moment Arm_{PT} is the moment arm of the patellar tendon (values obtained from dual energy x-ray absorptiometry scans).

**Muscle Anatomical Cross-Sectional Area.** The VL muscle aCSA was measured using real-time ultrasonography at rest. The aCSA was measured at 3 sites—25, 50, and 75% of the total femur length. Femur length was defined as the line passing from the greater trochanter to the central palpable point of the space between the femur and tibia heads when the knee was flexed at 90°. Echo-absorptive tape was placed at regular intervals (3 cm) along the muscle width at each site so that when the probe was placed on the leg, 2 distinct shadows were cast on the ultrasound image. Therefore, each ultrasound image provided a section of VL within the boundaries set by the 2 shadows and fascia surrounding the muscle. Each of these sections was analyzed for the total area using Image J to provide a total aCSA at that particular site. This method has been validated previously (40).

**Strength Measurement.** Maximal isometric knee extension torque was measured with the knee at a range of angles, that is, 30, 50, 60, 65, 70, 75, and 90° (full knee extension = 0°) on the right leg of all the participants. The order of testing by knee angle was randomized so as to minimize any systematic fatigue effect. After a series of warm-up trials consisting of 10 isokinetic contractions at 60°·s⁻¹ at 50–85% maximal effort, the participants were instructed to rapidly exert maximal isometric force against the dynamometer (Cybex NORM, Medway, MA, USA) lever arm. The participants were given both verbal and visual encouragement and feedback throughout their effort. Joint torque data were displayed on the screen of a Mac Book Air computer (Apple Computer, Cupertino, CA, USA), which was interfaced with an A/D system (Acknowledge, Biopac Systems, Santa Barbara, CA, USA) with a sampling frequency of 200 Hz. Isometric contractions were held for approximately 2 seconds at the plateau with a 60-second rest period between contractions. Peak torque was expressed as the average of data points over a 200-millisecond period at the plateau phase (i.e. 100 milliseconds either side of the instantaneous peak torque). The peak torque of 3 extensions was used as the measure of strength in each participant.
Statistical Analyses
Data were parametric and were therefore analyzed using a mixed-design repeated measures ANOVA. The within factor was the phase of training (i.e., weeks 0, 8, 10, and 12) and the between factor was training group (i.e., SR, LR, or Con). Post Hoc contrast analyses with Bonferroni corrections were used to compare data to baseline (“within” factor) and to control group (“between” factor). All data are presented as mean ± SEM. Statistical significance was set with alpha at ≤0.05. In terms of the sample size in this study, the average statistical power of the measured muscle parameters (CSA, pennation angle, fascicle length, and strength) was statistically adequate at beta = 0.86.

Repeatability of the Measurements. A small pilot study was conducted at the onset of the study on a similar population (i.e., age and physical characteristics). Repeated measures of VL muscle anatomical CSA, architecture, and strength on a group of 5 individuals (2 men, 3 women) were collected on 3 separate occasions. Within-day coefficients of variation (CVs in percent) of 1.5, 1.9, 1.3, 2.6, and 0.8%, and between-day CVs of 2.6, 2.1, 1.6, 2.9, and 1.8% were yielded for aCSA, fascicle length, fascicle pennation angle subcutaneous fat, and strength, respectively. Therefore, the repeatability of the measurements was within an acceptable range of error (3).

RESULTS
Total Training Load
To allow internal force comparisons, external training loads were monitored in each group. Total average loads (mean ± SD) lifted for externally loaded (i.e., not just using body mass) exercises completed were (a) Squat: SR 99 ± 10 kg, LR 80 ± 8 kg; (b) Leg Press: SR 60 ± 19 kg, LR 48 ± 17 kg; (c) Leg extension: SR 51 ± 17 kg, LR 46 ± 15 kg. To accurately assess internal muscle forces produced, the change in resistance moment arms of the CAM pulley machine used during leg extensions were also measured. Based on the training load for the leg extension exercise stated above for each group, the resistance machine load component yielded on average a 7% increase in external torque produced in the SR group compared with LR (SR: 137 vs. LR: 128 N·m).

The results in the subsequent sections describe paired physiological changes relative to baseline.

Muscle Anatomical Cross-Sectional Area at 25, 50, 75% Femur Length
The results at all femur lengths are presented in Table 3. The VL CSA increased significantly (p < 0.05) relative to baseline after training at all sites in both training groups. The significant training effect remained during the whole detraining period in both training groups at both 50 and 75% but was

| Table 3. Paired changes to VL CSA and pennation angle of fascicles at different femur lengths over the training and detraining phases.†‡ |
|---------------------------------|---------------|---------------|---------------|---------------|
| Site (% femur length)           | Baseline      | Week 8        | Week 10       | Week 12       |
| 25 CSA                          |               |               |               |               |
| SR 2,877 ± 338                  | SR 3,425 ± 303| SR 3,361 ± 306| SR 3,265 ± 310|
| LR 2,684 ± 127                  | LR 3,592 ± 303| LR 3,461 ± 309| LR 3,328 ± 295|
| Con 3,201 ± 253                 | Con 3,086 ± 259| Con 3,079 ± 240| Con 3,086 ± 259|
| 50 CSA                          |               |               |               |               |
| SR 3,033 ± 289                  | SR 3,699 ± 342| SR 3,526 ± 334| SR 3,382 ± 304§|
| LR 3,004 ± 385                  | LR 3,545 ± 339| LR 3,424 ± 349| LR 3,233 ± 333§|
| Con 3,326 ± 354                 | Con 3,314 ± 364| Con 3,294 ± 357| Con 3,314 ± 364|
| 75 CSA                          |               |               |               |               |
| SR 1,081 ± 175                  | SR 1,162 ± 127| SR 1,115 ± 127| SR 1,037 ± 119§|
| LR 1,074 ± 224                  | LR 1,505 ± 217§| LR 1,369 ± 200| LR 1,219 ± 191‡|
| Con 1,366 ± 165                 | Con 1,370 ± 185| Con 1,358 ± 175| Con 1,370 ± 185|
| 25 PEN                          |               |               |               |               |
| SR 10.1 ± 0.3                   | SR 10.3 ± 0.3| SR 10.6 ± 0.7| SR 9.9 ± 0.2|
| LR 10.2 ± 0.3                   | LR 11.2 ± 0.6| LR 11.6 ± 0.6| LR 11.0 ± 0.6|
| Con 11.9 ± 0.2                  | Con 12.0 ± 0.1| Con 12.0 ± 0.1| Con 12.2 ± 0.1|
| 50 PEN                          |               |               |               |               |
| SR 16.5 ± 0.5                   | SR 17.2 ± 0.3| SR 16.8 ± 0.9| SR 16.4 ± 0.4|
| LR 15.9 ± 0.2                   | LR 17.1 ± 0.8| LR 16.6 ± 0.8| LR 16.0 ± 0.6|
| Con 16.4 ± 0.8                  | Con 16.3 ± 0.7| Con 16.3 ± 0.7| Con 16.4 ± 0.7|
| 75 PEN                          |               |               |               |               |
| SR 16.0 ± 1.4                   | SR 17.9 ± 1.2| SR 16.8 ± 0.9| SR 16.8 ± 0.9|
| LR 15.5 ± 0.6                   | LR 17.5 ± 0.7| LR 17.2 ± 0.6| LR 16.3 ± 0.5|
| Con 19.4 ± 0.7                  | Con 18.5 ± 0.7| Con 18.4 ± 0.6| Con 18.5 ± 0.7|

*CSA = cross-sectional area; PEN = pennation; SR = shorter range of motion; LR = longer range of motion.
†Values are millimeters squared and degrees (mean ± SE).
‡Significantly different from other training group.
§Significantly above baseline.

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not evident at 25% of femur length after week 10. There was a trend for LR to exhibit greater relative gains in aCSA compared with SR at all sites, which was significant at week 8 at 75% of femur length. It was found that there was not only a main training effect ($p < 0.05$) but also a main group effect after week 8 ($p < 0.05$) with LR exhibiting a 59 ± 15% compared with SR showing 16 ± 10% increment in VL aCSA. Surprisingly, after the first 2 weeks of detraining, the group effect was no longer evident ($p = 0.07$) although both training groups were still significantly above baseline at weeks 10 and 12. There was no notable change over the 12-week period for the controls.

Muscle Architecture

Fascicle Pennation Angle—25, 50, 75% Femur Length. Table 3 shows the changes in fascicle pennation angle at each site for all 3 groups. At 25%, there was a main effect of training ($p < 0.05$) for each group, with no significant effect of group. Pennation angles recorded at baseline increased by 2 ± 5 and 9 ± 6% at week 8 for the SR and LR groups, respectively. However, by weeks 10 and 12, the effect of training was negated with values returning toward baseline ($p > 0.05$). This pattern was repeated at 50% of femur length with the main effect of training (5 ± 3% SR, 9 ± 3% LR) reverted after 2 weeks without the training stimulus. This was again the case for pennation angles at 75%; however, the significant increase because of the RT was observed until week 10 but had receded toward baseline after the 4 weeks of detraining at week 12.

Fascicle Length—25, 50, 75% Femur Length. There was a significant main effect of RT on fascicle length at all 3 sites (Figure 1, $p < 0.05$), which remained significantly elevated above baseline values after the detraining period, with both training groups significantly increasing ($p < 0.05$) fascicle length at all sites at weeks 8,
10, and 12 compared with controls. Although there was no group effect at 25%, a significant group effect ($p < 0.05$) did occur at both 50 and 75% of the femur length. The LR fascicle lengths increased 23 ± 5, 19 ± 4, 16 ± 4% at weeks 8, 10, and 12 from baseline in contrast to the SR group’s less pronounced increments of 10 ± 2, 6 ± 2, and 2 ± 2% during the same time period. All the values were significantly enhanced compared with baseline in both groups except for SR at week 12. At 75%, there was a similar significant ($p < 0.05$) group effect with relative increases of 19 ± 3, 13 ± 3, and 10 ± 2% at weeks 8, 10, and 12 for LR from baseline compared with 11 ± 2, 5 ± 4, and 2 ± 2% for SR during the same period.

### TABLE 4. Changes in quadriceps MVC over a range of knee flexion angles from baseline to week 8 (posttraining).

<table>
<thead>
<tr>
<th>Knee flexion angle (°)</th>
<th>Torque (N·m) baseline—week 8</th>
<th>Relative change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SR</td>
<td>LR</td>
</tr>
<tr>
<td></td>
<td>Relative change (%)</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>106–108</td>
<td>102–127</td>
</tr>
<tr>
<td>50</td>
<td>167–175</td>
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<td>212–225</td>
<td>202–247</td>
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<tr>
<td>75</td>
<td>218–215</td>
<td>193–232</td>
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<tr>
<td>90</td>
<td>216–218</td>
<td>161–208</td>
</tr>
</tbody>
</table>

*Significantly above baseline measures.

Muscle Strength. There was a main effect of training on the MVCs of both training groups ($p > 0.05$) at each of the training end ROMs, with SR recording an increase of 5 ± 10% at 5° and 30 ± 5% for LR at 90°. There were no differences ($p > 0.05$) between absolute MVC in SR and LR at baseline or after training. In agreement with previous observations after isometric joint-angle specific training, there was evidence of angular specificity of training in both the groups with SR significantly ($p > 0.05$) increasing MVCs at 50, 60, 65, and 70° (i.e., those closest to the training angle—Table 4), whereas LR increased MVCs over the entire angular range, that is, 30–90°. The angle of peak torque altered from 75 to 70° at week 8 in SR, where it remained for the duration of detraining in weeks 10 and 12. In LR, the angle of peak torque was originally 70° and did not change after training and detraining. By week 10, both groups displayed an average 6 ± 2% strength reduction (relative to the postrainning strength values), with SR not significantly above baseline (0 ± 2%) in contrast to LR remaining significantly above both baseline ($p < 0.05$) and SR ($p = 0.027$) at weeks 10 and 12. The control group’s strength did not significantly alter during the 12-week training and detraining period ($p > 0.05$).

### DISCUSSION

The current investigation aimed to study the in vivo effect of resistance exercise training and detraining over a larger ROM and hence longer average muscle length (0–90° knee flexion—LR) vs. a smaller ROM and hence shorter average muscle length (0–50° knee flexion—SR) on morphological, architectural, and functional changes in the VL. It was hypothesized that the group training over a wider range of joint angles (LR) would undergo a greater amount of skeletal muscle hypertrophy because of increased physiological stress and stretch on sarcomeres compared with the group training over a shorter range of joint angles (SR). It was also hypothesized that the LR group would still have a greater muscle mass after detraining, probably because of greater initial gains. Our findings partly support these hypotheses in that although there were no notable changes to any of the muscle parameters in the control group during a 12-week nontraining period, significant adaptations were observed in both SR and LR training groups ($p < 0.05$). This difference was not present at week 10 or 12 although both training groups had significantly less fat ($p < 0.05$) compared with that at baseline during the detraining period (7 ± 3% SL and 9 ± 1% LR).

**Subcutaneous Fat.** 25, 50, 75 Femur Length. The training intervention resulted in appreciable reductions in fat in both SR and LR training groups between weeks 0 and 8 ($p < 0.05$) at all measured sites. At 25%, the SR group reduced fat levels from 16.2 ± 3.9 to 15.6 ± 3.8 mm (−4 ± 1%), compared with LR (18.1 ± 4.0 to 15.4 ± 3.3 mm [−14 ± 3%]) posttraining; however, no group effect existed. After training ceased, both groups remained significantly lower than baseline at week 10 (−3 ± 2% SL and −9 ± 3% LR), but by week 12, there was no main effect of training and detraining on either group ($p > 0.05$), although there was a strong trend for a group effect at this time point ($p = 0.057$). The control group did not fluctuate significantly from baseline values during weeks 8, 10, and 12. There was also considerable subcutaneous fat loss at 50% after RT, with greater losses achieved by the LR group. Both lost 6.8 ± 1.2 mm after training; however, LR produced a loss of 22 ± 8% compared with SL with a 5 ± 2% loss at this phase of the protocol. The main effect of group remained during weeks 8, 10, and 12, as SR regressed toward baseline by week 12, whereas LR still possessed significant losses at this phase (−10 ± 6%). There was a similar trend seen at 75% where a main effect of both group and training existed at week 8.
Range-of-Motion Specific Muscle Loading

across all the muscle measurements. What is more, there was a significant main effect of training where strength, VL fascicle length, VL aCSA increased, whereas midhigh subcutaneous fat decreased to a greater extent after training at a longer muscle length compared with a shorter muscle length. Further, as per our expectation of greater physical demands of 1 training setup over the other, the stresses experienced by the knee extensors, although comparable in terms of an ecologically valid training program setting and in terms of absolute loads lifted were 10–25% greater in SR, in fact translated to approximately 32% greater internal stresses in the group training over the LR. This has a major impact on how both coach and athlete should view the impact of ROM on muscular adaptations. It is often tempting for an athlete to reduce joint ROM to accommodate a larger external load in the belief that lifting heavier will confer an advantage in adaptation. However, from the evidence presented, without an appreciation of internal muscle mechanics, this assumption would be erroneous.

The relative increases in VL size after 8 weeks of RT reported in this study (21 ± 8% in SR and 44 ± 13% in LR—averaged across the 3 sites) are much greater than those previously reported in a similar study (26). It should be however noted that this study (26) is the only other known study to our knowledge reporting changes specifically in VL size after training at shorter vs. longer muscle length (−11 ± 7% ST and −13 ± 12% LT—values estimated from Figure 2 in their Results section). The discrepancy between the 2 sets of results would not only arise from the differences between measurements of VL size (volume vs. aCSA) but also from the difference in training protocols (isometric vs. combined isoinertial and isometric) between Kubo et al. (26) and this study. Indeed metabolic cost and work done are greater during dynamic (i.e., concentric and eccentric) compared with isometric contractions (49). Therefore, a greater work-induced hypertrophic effect of the combined training may have produced the variation in hypertrophy gain differences between the 2 studies (11). Previous research on RT-induced whole quadriceps aCSA showed changes of 18.8 ± 72, 13.0 ± 72, and 19.3 ± 6.7 at distal, central, and proximal sites, respectively (34). It is nonetheless difficult to compare the studies directly, however, not only owing to the fact this study measured aCSA of the VL as opposed to all 4 quadriceps muscles but also the earlier report (34) showed a significant difference in hypertrophic response between the components of the quadriceps muscle group. In a review of hormonal responses and adaptations to exercise (24), the authors suggest exercises involving large muscle masses are superior to more isolated exercises to elicit greater hormonal responses. Therefore, the large mass exercises such as the bilateral squat in our study would elicit a greater hormonal response to that of a seated unilateral knee extension on a dynamometer as in the study of Kubo et al. (26).

Kubo et al. (26) estimated that internal VL force during isometric MVC at 100° of knee flexion was 2.3 times greater than that at 50°. This is key because mechanical stress magnitude is known to induce muscle hypertrophy (30). Using the IRM training loads, patellar tendon moment arm and aCSA, it was found that the mean force per unit area of muscle was 5.1 N·mm⁻² in the SL group compared with 6.8 N·mm⁻² in the LR group. The results of this study showed a nonsignificant trend for the LR group to exhibit a greater VL aCSA after RT compared with SR at each site. Importantly, in support of these beneficial morphological adaptations in the LR group, this group had a significantly greater increase in strength than SR group after training at all knee angles measured, which has previously been demonstrated after isometric training (26). In addition, Campos et al. (6) found that the subjects who trained with higher loads (i.e., 3–5 reps and therefore experiencing greater force) increased maximal strength more significantly than moderate (9–11 reps) or low (20–28 reps) loads, whereas the low to moderate repetition groups experienced the greatest hypertrophic gains in the 3 major fiber types (12.5–26%) after 8 weeks of RT. The above, in addition to previous work from Staron et al., shows that the hypertrophic training response is accompanied with a gradual transition in the percentage of fiber type and myosin heavy chain isoform (6,45), which may explain the disassociation between muscle strength and muscle size increments.

The magnitude of hypertrophy at 75% of the femur length was greater for LR after training. Relative increases were 59 ± 15% for LR and 16 ± 10% for SR, displaying evidence for region-specific hypertrophy. This has been observed previously after knee extensor RT (33,34,43). With both force generation and stretch being effective stimuli for muscle growth (14), the discrepancies in CSA between the groups may be because of regional differences in the total stimulus transmitted along the length of the muscle. Evidence exists that there is relatively high serial and parallel distribution of muscle fiber strain during transmission of myofascial force (17). Thus, the LR group could have experienced a greater strain at a more distal portion of the VL, which was also transmitted laterally, resulting in a greater stimulus and therefore enhanced hypertrophy at this site. Because muscle force is proportional to CSA, this provides a basis for enhancing the force output of the muscle, which is reflected in our strength results.

A major finding of this study was the greater increase in fascicle length at all sites in the LR group compared with SR group, although only significantly so at 50 and 75% of total femur length. In vivo increases in fascicle length are associated with the addition of sarcomeres in series (assuming a fixed sarcomere length) and appear to be strongly influenced by muscle length or stretch (12,46,50). A study by Boakes et al. (5) wherein surgery placed the thigh muscles under constant stretch to address a leg-length discrepancy, resulted in a 4-cm femoral lengthening. Fascicle and sarcomere length was measured in VL postoperatively and after 12 months. The results showed that in vivo fascicle length
increased and sarcomere length decreased, with sarcomere-genesis from approximately 25,000 to 58,650 as a result of adaptation to stretch. In this study, our protocol increased the muscle excursion range of the quadriceps to a greater extent in the LR group compared with that in the SR group. The results from this investigation support previous animal research evidence (22) that “average muscle length” (or excursion range) is a possible primary stimulus for increases in fascicle length in adult skeletal muscle. As previously mentioned, changes in fascicle length produce alterations to the force-velocity relationship in muscle (48) and could therefore impact on an athlete’s potential for power production.

Further architectural adaptations included a significant increase of pennation angle (P0) in both training groups (Table 3). A functional consequence of an increase in P0 is that more contractile material can be packed in parallel for a given anatomical cross-section (19,42). The P0 has been shown to increase after resistance exercise (1,4,20,39,43) and is usually closely associated with an increase in anatomical CSA in the quadriceps (42). Despite not reaching between-group significance, the average increase in P0 across the 3 sites was greater for LR than for SR (11 ± 5 vs. 7 ± 4%, respectively). Thus, this could also have been a factor in contributing to the LR group’s greater strength after training.

A further benefit experienced by the LR group was a greater reduction in subcutaneous fat at 50 and 75% of the femur length. In the athletic world, it is often considered beneficial to reduce levels of subcutaneous fat. For example, in running events (or events where the body is not supported), excess body weight has been shown to significantly decrease relative VO2max and performance during a running test as a direct consequence of an increased energy cost of running at submaximal speeds (8). Additionally, in sports where body mass is accelerated against gravity, a more lean muscle mass would be advantageous for performance and energetic consumption. This is not to mention the effect of body composition on cardiovascular risk factors and mortality for the average person (27). It would be tempting to suggest that the possible mechanism for an increased fat loss in the LR group may be linked to the greater internal physiological stress on the muscle, because strenuous resistive exercise may elevate postexercise metabolic rate for a prolonged period and may enhance postexercise lipid oxidation (31). However, more recently, Singhal et al. (44) found that there was no significant difference in postprandial lipemia in groups undertaking either moderate-intensity (MI) or high-intensity (HI) resistance exercise. An alternative explanation therefore for the physiological processes involved is linked with the fact that acute resistance exercise has been shown to increase adenosine monophosphate activated protein kinase (AMPK) activity (9), which in turn has also been shown to mediate effects of interleukin-6-stimulated increases in glucose disposal and free fatty acid oxidation. Further, AMPKα2 activity has been shown to be intensity dependent (7); therefore, training at longer muscle lengths could affect upstream factors of adiposity.

A second aim of the study was to determine if there was a differential response to detraining between the training groups. Both training groups showed that detraining period resulted in significant losses at weeks 10 and 12 (p = 0.001, p<0.05) in all measured parameters. Although generally there was no significant difference between groups, the LR group consistently exhibited a trend (p = 0.07, p<0.05) toward greater absolute and relative decrements in muscle dimensional parameters over the 4-week detraining period. This is in agreement with the findings of a previous study (47) that reported that after 12 weeks of RT, a group of older adults performing HI training increased total thigh CSA and strength to a greater (p < 0.05) extent than an MI training group did. After a subsequent 12 weeks of detraining, total relative thigh CSA and strength in the HI group diminished significantly more than that in the MI group. Despite these reductions, HI group strength and CSA remained significantly greater than in the MI group because of greater initial adaptations. In this study in terms of average VL aCSA across the 3 sites, there was a decrease from 44 ± 13 to 25 ± 11% above baseline between weeks 8 and 12 in the LR group, whereas SR decreased from 21 ± 8% at weeks 8–10 ± 7% at week 12. Therefore the relative changes in the aCSA to the LR group after 4 weeks of detraining (25 ± 11%) are still superior to those made by the SR immediately posttraining (21 ± 8%). This suggests that although greater initial gains may be lost at a greater rate, training using a relatively wider ROM may still confer an advantage for the longer term. This is evident in the strength data where the LR group was significantly stronger until the conclusion of the detraining period, whereas the SR group was not significantly stronger compared with the pretraining data, at week 10. It is difficult to say why greater gains are lost more rapidly, such as in the LR group, but it may be because of an inability to stimulate sufficient protein synthesis to support a larger muscle mass. One would not expect to observe a difference in daily protein synthetic rate between groups with no change in activity levels and dietary habits (21). Therefore, basal protein synthetic rates would support a greater relative percentage of a smaller muscle mass than a larger mass. Also, because resistance exercise causes perturbations to the intramuscular environment, and there are subsequent adaptations, a new homeostatic point is reached, where only a greater stimulus than the original will stimulate further adaptations (23). The LR group may have set a higher threshold to maintain adaptations, where daily activity did not disturb the internal muscle environment as much as in the SR group with a lower threshold. Indeed to reiterate, although the face value load was similar in the 2 groups (80% 1RM in both cases), the internal loads experienced are in fact greater under a relatively wide ROM, and therefore, because the phosphorylation of extracellular signal-regulated kinase 1 and 2 and the 38-kDa stress-activated protein kinase
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(p38) both appear to be intensity dependent (41) could be a contributing factor to the difference in cellular response and adaptation.

It should however be noted that in this study, although the ROM has been presented as different, the manner in which the 2 training groups were held to hold the contractions (over 2 seconds) means that the greatest difference in the loads experienced by the quadriceps muscle was because of the internal joint architecture. In other words, the difference between the 2 training protocols was not so much owing to the ROM (thought this differed at the start of the movement) but to the length of the muscle when the muscle group was experiencing the “isometric hold” phase of the exercise. Nevertheless, future studies should aim to determine whether in making the internal loads comparable the effects of training at the relatively elongated muscle length we describe here still exhibit the advantage over training at a relatively shortened muscle length. The authors do also recognize that in covering a greater ROM the muscle is loaded for a longer duration in LR (i.e., 0.25–0.50 seconds). However, previous studies (2) have concluded that measures of work production during RT do not directly scale with the adaptation responses seen in skeletal muscle. Furthermore, it is difficult to give substance to a mechanism whereby such a small difference in duration of loading (i.e., load-time product) would lead to serial sarcomerogenesis and give rise to such striking differences in fascicle length.

In summary, after 8 weeks of RT and 4 weeks of detraining on different ROM (and thus implied average muscle lengths), not only were there significant morphological differences between the 2 groups after training but also the muscle strength was enhanced to a greater extent after training at a larger rather than a narrow ROM. Moreover, there was a significant difference between groups in muscle architecture, with fascicle length increments greater when training over a large ROM, supporting the notion that muscle length (or excursion) has a major influence on fascicle length. The implications of the results may be useful in athletic training and also deter athletes from reducing their ROM during exercises to accommodate greater external loads.

**Practical Applications**

In the field of practice, when choosing an ROM in which a resistance exercise should be performed, muscle mechanics must also be considered. We have shown that RT protocols that enforce a wider ROM enhance the muscle characteristics that influence force and power production to a greater extent than protocols where the ROM is not as extensive. A common error in practice is allowing the ROM to be compromised to accommodate a greater absolute external load, in an attempt to increase the stress of mechanical loading. Following this, it is important for the coach to reinforce a more complete ROM, even when absolute load maybe reduced, to provide a greater internal stress and more potent stimulus for adaptation. Optimization of training mechanics could therefore potentially reduce the time spent in the gymnasium achieving sporting and performance goals, because training time and exercise volume constraints are pivotal considerations in the periodization of training. Adherence to a greater ROM also provides a better long-term prognosis for retention of training adaptations, for example, after prolonged bed rest and immobilization (caused by illness and injury) or indeed during tapering.

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**References**


