The effects of immobilization, after lower leg fracture, on the contractile properties of human triceps surae

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Summary
1. The contractile properties of the triceps surae were evaluated in 11 patients after unilateral fracture of the lower leg and subsequent immobilization for 135 ± 68 days. Calf muscle cross-sectional area (plus bone: CSA) was assessed from anthropometric measurement.

2. It was shown that the injured leg had a faster time to peak tension and increased half-relaxation time (1/4RT); twitch force (P1) was reduced by 25%. Evoked maximal tetanic tensions (P0) at 10 and 20 Hz were reduced by 51% and 46% respectively compared with the uninjured leg. The force of a maximal voluntary contraction (MVC) was also reduced, by 50%, but calf circumference and CSA were only 5% and 16% respectively lower in the injured leg.

3. It was concluded that the changes in contractile speed may indicate a relatively greater atrophy of slow (type I) muscle fibres.

4. The relationship between CSA and tension generation in the injured limb was shown to be poor after immobilization and during recovery. Anthropometric estimation of CSA does not appear to reflect the degree of muscle wasting, as indicated by reduced tension development after immobilization.

Key words: anthropometry, atrophy, contractile properties, electrical stimulation, immobilization.

Abbreviations: CSA, cross-sectional area; MVC, maximum voluntary contraction; 1/4RT, half-relaxation time; TPT, time to peak tension.

Introduction
It is now well established that complete limb immobilization produces muscle atrophy and weakness. In animals the degree of wastage has been assessed directly from changes in muscle weight and cross-sectional area, and by the reduction in strength from electrical stimulation of the muscle. In man, loss of limb bulk by anthropometric, computerized tomography and ultrasound measurements has been demonstrated [1-3], and results from the latter techniques reflect the decrease in fibre area of biopsy samples of atrophied human muscle [4, 5]. However, there have been no direct measurements of the contractile properties of immobilized muscle in association with observed changes in size in man. The aim of the present investigation was to measure the electrically evoked twitch and tetanic characteristics of human triceps surae after immobilization, and relate the changes to anthropometric estimates of the cross-sectional area of the muscle.

Methods
The subjects were 11 servicemen aged 21.8 ± 3.0 years. All had suffered unilateral fracture of tibia and/or fibula, and were recruited while at the Joint Services Medical Rehabilitation Unit, R.A.F. Chessington, between January and July 1982. They first visited the laboratory 36 ± 21 (range 10-72) days after becoming weight bearing on the injured leg, and had been immobilized 135 ± 68 (range 46-278) days. The subjects were habituated
to the electrical stimulation techniques after a minimum of four separate visits to the laboratory during an initial 2 week period. Cross-sectional measurements of the contractile properties of the triceps surae muscles of both legs were then made on the 11 subjects. During the following months subjects were measured longitudinally until discharge from J.S.M.R.U.

The apparatus used to measure the electrically evoked contractile characteristics of the triceps surae has been described in detail [6]. It consisted of an isometric dynamometer in which the subject sat with thigh horizontal and ankle at 85°. A clamp placed on the thigh above the knee transmitted upward force produced by contraction of the triceps surae to a transducer, the output of which was displayed on a u.v. recorder and oscilloscope.

Contractions of the triceps surae were electrically evoked by the application of square wave pulses through two 8 cm x 12 cm foil in tissue electrodes, one placed over the heads of the gastrocnemius, the other (cathode) over the belly of the soleus. Twitch responses were elicited with single pulses of 50 or 100 μs duration, increasing in voltage each time, and 30 s was allowed between pulses. Voltage was increased until maximal responses were obtained; maximum twitch tension ($P_t$), time to peak tension (TPT) and time to half relaxation ($\frac{1}{2}RT$) were recorded. Repetitive stimuli at frequencies of 10, 20 and 50 Hz were applied in a 6 s train, 2 s at each frequency, and a 1 min rest was allowed between trains. Again voltage was increased after each train, until maximal responses were obtained or the subject could tolerate no further increase when habituating to the procedure. Maximal responses were taken as those agreeing within ±5% after three successive increases in voltage. After the tetanic stimulation subjects rested for 2 min, then performed three maximal voluntary contractions at intervals of 30 s, the best of the three being reported. After a further 2 min rest an evoked fatigue test was performed involving 20 Hz tetanic stimulation at a maximal voltage lasting 330 ms and repeated once every second for 2 min.

Anthropometric measurements were made with the subject standing, before or at least 45 min after the stimulated contractions. Leg circumference was first ascertained at the widest point on the calf with a metal tape measure; the height of this circumference from the ground was noted and all subsequent circumferences were measured at this position. Skinfold measurements were made medially and laterally with standard calipers and corrected after the method of Jones & Pearson [7] before use in the calculation of muscle and bone cross-sectional area (CSA).

**Results**

All subjects tolerated maximal tetanic stimulation of the uninjured limb after two or three visits to the laboratory, but they were more protective of their injured leg and required at least a further two visits to habituate this limb to the involved procedure. In three subjects, however, maximal tetani could not be achieved, although maximal twitch responses were perfectly acceptable.

Table 1 shows the mean ± 1 SD values obtained from injured and uninjured limbs on the first occasion the patients were able to tolerate maximal tetanic stimulation of their injured limb, or in the three cases where this was not possible when maximal tetani were first evoked from the uninjured limb. The half-relaxation time ($\frac{1}{2}RT$) of the triceps surae was significantly increased, but the TPT was significantly reduced in the injured limb, and $P_t$ was decreased by an average of 25%.

**TABLE 1. Comparison of values obtained from uninjured and injured limbs on the first occasion maximal tetanic stimulation was tolerated**

<table>
<thead>
<tr>
<th></th>
<th>TPT (ms)</th>
<th>$\frac{1}{2}RT$ (ms)</th>
<th>$P_t$ (N)</th>
<th>$P_{010}$ (N)</th>
<th>$P_{020}$ (N)</th>
<th>MVC (N)</th>
<th>FI</th>
<th>CSA (cm²)</th>
<th>Circumference (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uninjured</td>
<td>118 ± 16</td>
<td>92 ± 14</td>
<td>114 ± 31</td>
<td>696 ± 207</td>
<td>1032 ± 197</td>
<td>1462 ± 198</td>
<td>0.66 ± 0.16</td>
<td>89.2 ± 13.9</td>
<td>37.0 ± 2.8</td>
</tr>
<tr>
<td>Injured</td>
<td>88 ± 16</td>
<td>108 ± 16</td>
<td>86 ± 32</td>
<td>353 ± 87</td>
<td>558 ± 126</td>
<td>738 ± 214</td>
<td>0.70 ± 0.15</td>
<td>74.8 ± 11.3</td>
<td>35.0 ± 2.6</td>
</tr>
<tr>
<td>Significance</td>
<td>**</td>
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<td>N.S.</td>
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Electrically evoked $P_t$, twitch tension; TPT, time to peak tension; $\frac{1}{2}RT$, half-relaxation time; $P_{010}$, tetanic tension at 10 Hz; $P_{020}$, tetanic tension at 20 Hz; FI, an index of fatigue; MVC, maximal voluntary contraction; 'circumference' indicates maximal calf circumference; CSA, cross-sectional area of muscle plus bone estimated anthropometrically. Significance: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$. N.S., Not significant.
The mean tetanic tensions at 10 Hz ($P_{10}$) and 20 Hz ($P_{20}$) were significantly ($P < 0.001$) decreased by 51% and 46%. This resulted in twitch tetanus (at 20 Hz) ratios ($P_1/P_{20}$) of 0.11 and 0.15 in the uninjured and injured legs respectively. MVC was reduced by an average of 50% in the injured limb compared with uninjured, reflecting the reductions in $P_{10}$ and $P_{20}$ (Fig. 1). Injured limb circumference was significantly reduced by an average of 5% when compared with the uninjured limb, but CSA minus skinfold thickness (muscle plus bone) was reduced by 16% in the injured limb. There was no significant difference between the fatigue index of the injured and uninjured limb, nor was there any correlation found between length of immobilization and the reduction in twitch, tetanic or maximum voluntary force of the injured limb. However, the reduction ($\Delta$) in injured limb TFT was related to duration of immobilization ($t$). The relationship is given by the equation:

$$\Delta_{\text{TFT}}(\%) = 15.5 + 0.0971t \text{ (days); } (r = 0.59)$$

Fig. 2 shows the relationship between calf CSA and $P_{20}$ for injured and uninjured limbs on the first occasion maximal tetanic stimulation was tolerated on the injured limb. It will be noted that whereas the uninjured limb $P_{20}$ was associated with CSA ($r = 0.47$) and closely related to previously established values, the points for the injured leg lie below and are unrelated to the expected relationship for normal men. MVC showed considerably more variation than $P_{20}$ and a reduced association ($r = 0.28$) with CSA in the uninjured limb. The MVC and CSA of the injured leg were not significantly ($P > 0.1$) correlated (Fig. 3). In three subjects who were measured longitudinally (see the Methods section) both $P_{20}$ and MVC of injured limb increased towards the values obtained in the uninjured leg. These increases were disproportionate to the change in CSA; indeed in one of the three subjects CSA remained constant through the period of rehabilitation (Figs. 2 and 3). The measurements of $P_{10}$ showed the same pattern of change as $P_{20}$ in both legs, and a similar relationship to CSA after injury.

**Discussion**

One of the major problems in assessing muscle strength after limb fracture and its recovery is overcoming the patient’s fear of re-fracture. In the present study the patients had been weight bearing on the injured limb between 10 and 72 days before the stimulation techniques were applied, but they were still wary of any use of their injured limb, even though undergoing a well supervised rehabilitation programme. For this reason the habituation of the subjects to the evoked contractions took longer than the two or three visits.

**FIG. 1.** Relationship between MVC and $P_{20}$ for ○, uninjured and ●, injured limbs. The continuous line is the regression ($r = 0.92$), for 30 subjects previously measured, of a range of limb sizes. Note that $P_{20}$ and MVC are still related in the injured limbs in the present study.
Fig. 2. Relationship between $P_{0.20}$ and CSA in uninjured (○), injured (●) and recovering (■) limbs. ---, Regression line, for 59 subjects previously measured, of differing limb sizes ($y = -38.48 + 12.78x; r = 0.88, n = 59$); ---, uninjured limb regression line in the present study ($y = 430.9 - 6.73x; r = 0.47, n = 11$).

Fig. 3. Relationship between MVC and CSA. Symbols are identified in Fig. 2. ---, Regression for 91 subjects previously measured ($y = -183 + 20.94x; r = 0.92, n = 91$); ---, uninjured limbs regression line in the present study ($y = 1107 + 398x; r = 0.28, n = 11$).
required under normal circumstances, and, therefore, the initial values for the contractile properties in Table 1 were measured between 17 and 86 days after the patients’ limbs were weight bearing. Nevertheless, a relationship between reduction in TPT and duration of immobilization persisted, though no relationship between length of immobilization and any of the other measured variables was found (cf. [4]). The reduced TPT of the injured limb relative to the uninjured limb may indicate a general shift in the whole fibre population of the triceps surae towards a faster contractile speed, but if this were so then one would expect a reduction rather than an increase in ½RT (Table 1). A further possible cause of a decrease in TPT is decreased compliance of the system after immobilization, which might also explain the increased twitch tetanus ratio observed, though ½RT would also decrease. However, a crude measure of muscle compliance made by moving the foot from full plantar flexion to full dorsiflexion showed that similar forces were required to move both feet in the subjects measured. The measurements were made with knee at right angles and lower leg horizontal, and a spring balance attached to a strop was looped round the ball of the foot and used to pull the foot upright. A more likely explanation of the TPT change in the injured limb is a relatively greater atrophy of slower motor units, which make up the majority of the triceps surae [8], as demonstrated in human quadriceps [9, 10] and in rat gastrocnemius and soleus [11, 12]. A loss of force attributable to slow motor units will reduce $P_o$ and thus increase the relative contribution of faster firing units to force production and result in a decreased TPT (Fig. 4). Since slow units will still produce some force the relaxation phase of the twitch, though at a lower force, will follow the same time course as normal, consequently ½RT will be maintained or increased [13] and total contraction time will be unchanged. Fig. 4 shows actual twitch records from the injured and uninjured legs of one individual, illustrating reduced TPT, increased ½RT and maintained total contraction time in the injured limb. The reduced TPT in injured limbs may account for the slightly greater mean reduction in $P_o$10 of 51% compared with 46% in $P_o$20, since fusion frequency would be expected to rise. That muscle forces, $P_o$, $P_o$10, $P_o$20 and MVC are reduced by immobilization is incontrovertible (Table 1); however, the relationships of the measured forces to estimates of muscle dimensions are not so clear. On theoretical grounds muscle force and CSA must be related, and Fig. 2 shows that $P_o$20 and the best estimate of CSA that can be made anthropometrically, calf CSA (muscle plus bone), normally correlate well ($r = 0.88$), as indicated by the full line. Uninjured limb $P_o$20 and CSA also correlate, $r = 0.47$ (dotted line), with points distributed around the ‘normal’ line. However, injured limb $P_o$20 and CSA are not associated, and the scatter of points is below the normal line. The distribution of points for the injured limb may be due, in part, to our anthropometric method for estimating CSA. Recent studies using ultrasonography [3] and computerized tomography [2] have shown that gross measurements of muscle bulk can seriously underestimate the degree of atrophy within specific muscles of the leg. If this is the case in the present study then the simplest explanation for the reduction of $P_o$20 by an average of 2.88 times as much as limb CSA (muscle plus bone) in the injured limb, lies in the overestimation of the CSA of the force-producing muscles.

![Fig. 4](image-url)
However, Häggmark [1] found that after 6 weeks of immobilization computerized tomography revealed a similar percentage decrease in the calf muscles CSA as in the lower leg (muscle plus bone) CSA. These findings imply that the changes in injured limb CSA (muscle plus bone) in the present study do reflect the changes in calf muscle CSA and that the reason for the injured limb values in Fig. 2 lying below the normal line is a decreased specific tension. This has been shown in rat soleus [14, 15] and in cat gastrocnemius and soleus after tenotomy [16].

The relationship between the injured leg MVC and CSA (Fig. 3) must therefore be doubtful for the same reasons as for $P_{0.20}$ and CSA. In fact no correlation was found between MVC injured and CSA injured. However, the measurement of MVC on the injured limb appears to be a reliable indicator of muscle strength, as the mean fall in injured leg MVC is similar to the mean fall in $P_{0.20}$, 50% and 46% respectively of uninjured leg values, and, as Fig. 1 shows, MVC and $P_{0.20}$ are still normally related after immobilization though the absolute values are lower. It must be remembered, however, that the subjects had habituated to the involved procedures over several weeks, and had become confident of using their injured limb by this stage. At earlier stages of rehabilitation injured leg MVC may not be a proper indication of muscle force-generating capability, owing to fear of re-fracture and consequent lack of motivation.

In the subjects who were measured longitudinally it can be seen that both $P_{0.20}$ and MVC can approach normal values after 9-11 weeks of measurement (Figs. 2 and 3). In fact in one subject $P_{0.20}$ of the injured leg was within the normal range of values, and equal to that of the non-fractured limb. However, the injured leg MVC still did not match that of the uninjured leg, even though the subject was well motivated and training hard. This may indicate that a neural 'learning' has to take place before the maximum voluntary force can be generated [17, 18]. CSA increases are not so marked in all cases; indeed substantial increases in $P_{0.20}$ and MVC are clearly possible without measurable increase in limb CSA (muscle plus bone), further highlighting the unsuitability of this measurement in assessing rehabilitation after lower limb immobilization.

References


