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Evaluation of extensibility, passive torque and stretch reflex responses in triceps surae muscles following serial casting to correct spastic equinovarus deformity

B. J. SINGER, K. P. SINGER and G. T. ALLISON

Centre for Musculoskeletal Studies, Department of Surgery, The University of Western Australia, Perth, Western Australia

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Primary objective: Spastic equinovarus deformity of the ankle in adults with acquired brain injury can severely limit the achievement of rehabilitation goals. This study examined changes in triceps surae muscle extensibility, passive resistive torque and soleus stretch reflex responses in 10 adult brain injured subjects undergoing serial casting to correct ankle equinovarus deformity.
Method: Goniometric measurement of maximal passive dorsiflexion was used to evaluate extensibility of the triceps surae muscles. Computer controlled ankle dynamometry and surface electromyography were used to identify passive resistive torque and soleus stretch reflex onset angle in response to stretches at two velocities.
Results: The mean casting period was 5 weeks. Casting was discontinued in one subject due to failure to achieve measurable gain in ankle range over three consecutive cast changes. Median improvements in maximal ankle dorsiflexion, with the knee flexed or extended, of 30° and 15°, respectively, were achieved in the remaining nine subjects ($p < 0.0001$). The median passive ankle range in response to a displacing torque of 10 Nm increased 4.3° over the intervention period ($p < 0.0001$). Consistent soleus reflex activity in response to passive stretches at $25^\circ.s^{-1}$ was elicited in only four subjects. A trend for the stretch reflex onset to move further into the available range was demonstrated in these subjects.
Conclusion: In the present study, serial casting contributed to significant change in triceps surae extensibility and passive resistive torque, corresponding with improved maximal passive ankle dorsiflexion range and an increase in the angle achieved with a displacing torque of 10 N.m. Increased stretch reflex threshold was observed in some subjects. The use of pre-determined outcome criteria and careful measurement of responses to this intervention were important to prevent premature discontinuation of casting when gains were slower than expected.

Introduction

Following adult onset acquired brain injury (ABI), secondary musculo-skeletal complications, associated with imposed immobility and neuromuscular dysfunction, may arise [1, 2]. In particular, 'spastic equinovarus deformity' of the ankle is a commonly reported secondary complication of brain injury [3]. Equinovarus deformity of the ankle can profoundly limit mobility due to altered lower limb alignment during weight-bearing tasks.

Correspondence to: B. Singer, The Centre for Musculoskeletal Studies, Department of Surgery, The University of Western Australia, Level 2, MRF Building, Rear 50, Murray Street, Perth, Western Australia 6000. e-mail: kps@cms.uwa.edu.au

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Historically, this deformity has been considered to result principally from plantarflexor/invertor muscle overactivity. Such muscle overactivity can take a number of forms including exaggerated stretch reflex responses, inappropriate co-contraction of antagonist or synergistic muscles and sustained dystonic muscle activity producing abnormal joint postures [4]. Increasingly, evidence points to the potential for non-reflex changes within the musculo-tendinous unit to also contribute significantly to the development of equinovarus deformity following brain injury [5–7].

Non-reflex changes may comprise loss of extensibility of the triceps surae muscles, associated with reduced ankle range of motion; in addition to reduced compliance, such that greater force is required to achieve passive lengthening. Changes associated with immobility and disuse, especially in predominantly slow twitch muscles such as soleus, have been well documented in animal experimental models [6, 8–10] and, to a lesser extent, in humans [11, 12]. Disuse induced responses include reduction in muscle fibre size and strength production, increased intramuscular collagen and focal degeneration at the musculo-tendinous junction (reviewed by [6, 9]).

When muscle is maintained in a shortened position it rapidly loses extensibility and becomes less compliant [13–15]. This may result in 'fixed contracture', where limited or no passive range of motion is available. Repeated or sustained muscle contraction has been shown experimentally to exacerbate loss of muscle extensibility [16, 17]. It seems likely that plantarflexor muscle overactivity following brain injury could contribute to the development of muscle shortening, which may in turn exacerbate abnormal stretch reflex responses. Extrafusal muscle fibre resting length can influence spindle sensitivity and rate of discharge [18], which may account, in part, for the observed interaction between loss of muscle extensibility (contracture) and stretch reflex hyper-excitability (spasticity) [19, 20]. In addition, abnormal actin-myosin cross-linkages have been postulated to contribute to increased passive muscle stiffness in neurologically impaired individuals [21].

A range of physical treatments directed at restoring triceps surae muscle extensibility and ankle joint range of motion have been used therapeutically [22, 23]. One of the most commonly used interventions is 'serial casting'. Serial casting refers to the repeated application of plaster of Paris (POP) casts in order to stretch the soft tissues which limit joint range [24]. It has been asserted that serial casting can also modulate muscle overactivity and reduce reflex hyper-excitability [25]. Although there is some evidence for the efficacy of serial casting to correct spastic equinovarus deformity [23, 26, 27], the mechanisms via which improvements are achieved remain to be elucidated [28].

Objectively quantifiable changes have been reported in triceps surae muscle stiffness (passive resistive torque) and stretch reflex threshold (angle of onset of electrical activity in a previously relaxed muscle), following a serial casting regime, in children with cerebral palsy (CP) [29–32] and idiopathic toe walkers [33]. There do not appear to be any published investigations of the influence of serial casting on passive torque and reflex responses in triceps surae muscles following serial casting in brain injured adults.

The present study sought to examine changes in triceps surae extensibility, passive torque and stretch reflex threshold associated with the serial application of below knee plasters to correct spastic equinovarus deformity in adults with ABI.

Materials and methods

Subjects

Individuals who were admitted to the Neurosurgical Rehabilitation Unit at Royal Perth Hospital, Perth, Western Australia, were prospectively screened. Subjects were considered suitable for casting if they met the following criteria: (i) they were neurologically stable, and able to co-operate with the casting regime, (ii) a plantigrade (right angle) position was unable to be achieved in one or both ankles when maximal passive stretch was applied with the knee extended, or progressive decrease in ankle range of motion (greater than 5° measured via clinical goniometry) was demonstrated over 3 successive weeks, and/or (iii) moderate-to-severe abnormal equinovarus posturing of the ankle prevented a normal placement of the foot during weight-bearing tasks.

In the case of a bilateral presentation, the most severely affected limb was treated initially. Contraindications to casting, including skin abrasions or lacerations in the area to be casted, precluded entry to the study. Approval was obtained from the Royal Perth Hospital Ethics committee and all subjects, or their guardian, gave informed consent prior to enrolment in the study. In addition to the serial casting regime, all subjects participated in individualized therapy programmes as determined by the Rehabilitation Team.

Ten subjects with brain injury secondary to trauma, extensive intracerebral or subarachnoid haemorrhage or complications associated with surgical removal of intracerebral tumour underwent serial casting for equinovarus deformity over a period of 1 year. Five subjects in the present series were enrolled in a randomized controlled trial to examine the effect of the addition of Botulinum toxin Type A (BTXA) to serial casting. These subjects received either an additional injection of placebo or BTXA, while the other five received serial casting only. Initially, data were analysed according to 'casting' or 'casting plus adjunctive treatment' subgroups; however, as no differences were found between means for any of the derived variables, data were pooled. Information about the cohort is outlined in table 1. Three of the 10 subjects were female. Ages ranged from 18–48 years. The mean casting period was 5 weeks (range 3–10). Casting was discontinued in one subject due to failure to achieve any measurable gain in range over three successive casts. In one subject, EMG data were not collected on every test occasion. Consequently, the data presented reflect nine subjects (extensibility and passive resistive torque) and eight subjects (EMG), respectively.

Measures

Measurement of triceps surae muscle extensibility

Goniometric measurement of maximal ankle passive range of motion (PROM) with the knee flexed was considered to reflect primarily soleus muscle extensibility, while maximal ankle PROM with the knee extended was considered to represent extensibility of the gastrocnemius muscle [34, 35]. A standardized protocol was used to measure maximal passive range of ankle dorsiflexion motion using defined bony landmarks [36]. All measures were undertaken by the same two physiotherapists. Subjects were positioned with both limbs supported in $\sim 30^\circ$ of knee flexion over a wedge, and encouraged to relax. One therapist grasped the heel firmly, taking care

Table 1. Subject demographic information with principal diagnosis following acquired brain injury, criteria for casting and the number of casts

Subject	Age	Time since injury (months)	Diagnosis	Number of casts	Criteria for casting
1	20	3	Stroke post tumor removal	3	Severe dystonic equinovarus, decreasing PROM
2	34	4	SAH, secondary to aneurysm	9	Extensor dystonic posturing with contracture
3	42	6	SAH, secondary to aneurysm	5	Extensor dystonic posturing with contracture
4	35	4	Stroke, secondary basilar artery embolus	10	Extensor dystonic posturing with contracture
5	18	4	CHI—diffuse axonal injury	5	Decerebrate posture, bilateral contracture
6	48	2	ICH, with secondary empyema	6	Extensor dystonic posturing with contracture
7	20	3	Embolic stroke	3	Severe dystonic equinovarus, decreasing PROM
8	25	3	SAH, secondary to aneurysm	3	Severe dystonic equinovarus, decreasing PROM
9	34	6	SAH, secondary to aneurysm	3	Extensor dystonic posturing with contracture

SAH = subarachnoid haemorrhage, ICH = intra-cerebral haemorrhage, CHI = closed head injury, PROM = passive range of motion, POP = Plaster of Paris.

to maintain neutral calcaneal alignment, and applied a maximal dorsiflexing force to the plantar surface of the foot (figure 1(*a*)). At the perceived end of range, pressure was maintained for a few seconds, until no further motion was detected. Two measurements were taken of the ankle angle using a universal goniometer, and the average utilised for subsequent analysis. The measurement procedure was repeated with the knee extended. Both limbs were evaluated on each test occasion.

Measurement of passive resistive torque

A computer controlled torque measurement system was developed to evaluate resistance of the triceps surae muscles and associated soft tissues to slow passive stretch. Passive rotation of the ankle was achieved using a linear actuator, and the excursion monitored via optical sensors. Limits were pre-programmed to prevent excessive stretching of the soft tissues. Subjects were positioned in modified supine lying with their hips and knees flexed to $\sim 90^\circ$ (figure 1(*b*)). The lower limbs were secured in place and the centre of rotation of the footplate was aligned with the subject's medial malleolus, to approximate the ankle joint axis [37]. Initially, stretches of increasing excursion were applied from a start position of 20° plantar-flexion to the maximum available range of dorsiflexion, as defined by loss of heel contact with the footplate. Once the available range of motion for the individual was determined, data were acquired from several passive stretches at a velocity of $5^\circ.s^{-1}$. A minimum rest of 8 seconds duration was allowed between each stretch cycle.

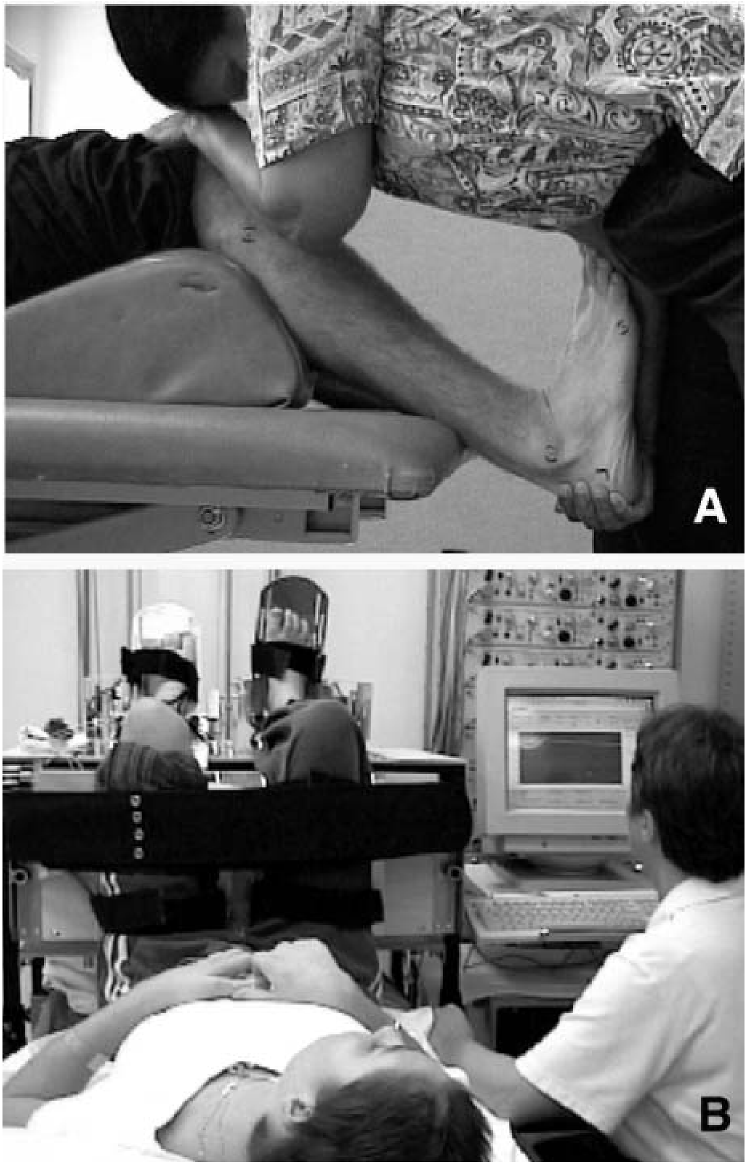

Figure 1. *Standardized goniometric assessment of maximal passive ankle dorsiflexion range was performed using the angle of intersect of lines derived from four bony landmarks (the head of the fibular to the lateral malleolus and the anterio-inferior borders of the calcaneus to the head of the fifth metatarsal) (a). Computer controlled ankle dynamometry was used to allow simultaneous acquisition of force-displacement and EMG data in response to passive stretches at velocities of 5 and 25°.s^{-1} (b).*

Measurement of stretch induced muscle activity

Surface electromyography (EMG) was used to detect activity of the tibialis anterior and medial soleus muscles during the passive stretches. To minimize skin impedance, the electrode area was shaved and an abrasive skin preparation paste used (skinPure, Nihon Kohden, Japan). Pairs of 10 mm diameter disposable Ag/AgCl electrodes (Red Dot 2239, 3M, Ontario, Canada) were placed on the respective bellies, in line with the muscle fibres, with an inter-electrode distance of 25 mm. A ground electrode was placed on the medial malleolus. To detect reflex responses, data from at least two passive stretch cycles at a velocity of $25^{\circ}.s^{-1}$ were collected from 20° plantarflexion to maximal available dorsiflexion.

Raw data from the strain gauges, position sensors and surface electromyography were sampled at 1000 Hz and stored to disc. EMG recordings were bandwidth filtered at 6–400 Hz. All force and EMG outputs were assessed visually during data collection and any test cycles containing voluntary muscle activity, which resulted in obvious distortion of the smooth shape of the force-displacement curve, were rejected.

Casting procedure

Subjects were positioned in prone lying for application of the plaster cast, wherever possible. The initial below knee cast was applied without any tension on the soft tissues, to accustom the subject to the sensation of immobilization. Subsequent casts were applied with the triceps surae muscle and associated soft tissues maximally tensioned. Where there was a major inversion component to the deformity, this was corrected prior to attempts to gain dorsiflexion range. Two therapists were involved in each cast application. Following protection of potential areas of localized pressure with silicon gel segments, a POP back-slab was moulded to the foot and calf area and 10 cm POP bandages were applied circumferentially to fashion the cast. Finally a fibreglass-impregnated wrap was applied for added strength [36]. Casts were re-applied on a weekly basis.

A desired outcome for the casting regime was the achievement of 10° of ankle dorsiflexion, with the knee extended, as this range was considered necessary to prevent premature heel-off during gait [38, 39]. Casting was continued until this criterion was achieved or no measurable gain (less than 5° as measured by goniometry) of maximal passive range was recorded over three consecutive plaster changes. In addition, subjects were withdrawn from the casting programme if there was evidence of developing pressure areas or skin breakdown. The final cast utilised a malleable splinting material, which could be bi-valved for use as a resting splint to maintain the range of ankle motion as required.

Experimental design

Prior to commencement of casting, a series of baseline goniometric measures were performed to establish the stability of maximal passive range of ankle motion. Subsequently, data were collected on a weekly basis in conjunction with every plaster change. Data used in the analysis represented five standard points in the casting regime, namely: prior to application of the first POP cast (pre), following removal of the first cast (initial), at the mid point of the series (mid), following removal of the final cast (end), and 3 months from commencement of the casting regime (post). An audit was conducted 6 months following commencement of the casting regime to determine the longer term functional mobility status of the participants.

Reliability

Test-re-test reliability of the goniometric and passive torque measures utilised in this investigation produced intraclass correlation coefficients (ICC) of 0.88 and 0.98, respectively. Test–re-test reliability of the method used to visually determine the angle of EMG onset was performed on data from the five measurement occasions. This also demonstrated acceptable values (ICC = 0.85–0.97).

Data analysis

The raw torque and angle data were calibrated and filtered (4th order Butterworth low pass, 6 Hz) and zero offsets were removed. Torque-angle curves were constructed and customized software developed to determine the point on the curve (angle) that coincided with torques of 5 and 10 N.m (figure 2).

Electromyographic data from medial soleus and tibialis anterior muscles were full wave rectified and filtered at 30 Hz. Muscle activity in both the muscle being passively stretched (triceps surae) and the muscle undergoing shortening (tibialis anterior) was examined using a visual method of onset determination. The angle of onset of sustained electrical activity in a previously relaxed muscle was considered to represent stretch reflex threshold.

Due to the small sample size, non-parametric Friedman two-way analysis of variance by ranks was used to examine change over time in the following derived variables:

- maximal passive range of dorsiflexion motion (knee flexed and extended),
- angle achieved at torques of 5 and 10 N.m during stretches at $5^{\circ}.s^{-1}$, and
- reflex threshold angle during stretches at $25^{\circ}.s^{-1}$.

On all statistical tests, $p < 0.05$ was adopted as the criterion for recording significant differences.

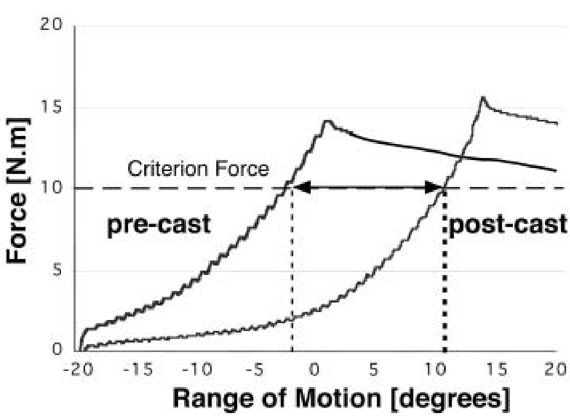

Figure 2. Torque-angle curves were constructed from raw data and customized software was used to determine the point on the curve (angle) that coincided with a displacing torque of 10 Nm. The torque-angle curves shown were constructed from data obtained prior to commencement of the casting regime (pre) and following removal of the final cast (end). The horizontal arrow depicts the change in angle, reflecting reduced passive resistive torque over the casted period.

Results

The pooled results are summarized in table 2. Significant differences were obtained over time for the muscle extensibility and passive torque variables ($p < 0.0001$). In cases where consistent reflex thresholds were detected, inspection of the trends demonstrated temporal improvement in the onset angle.

Triceps surae extensibility

Results of repeated goniometric evaluation of maximal PROM (knee flexed or extended) for the nine subjects studied are presented in figure 3. The trend for a decrease in maximal PROM over three baseline measures prior to the intervention was evident in most subjects (figures 3(*a*) and (*b*)). Following casting, all subjects achieved at least 10° dorsiflexion with the knee flexed (figure 3(*a*)), whilst six of the nine subjects achieved a maximal PROM of 10° dorsiflexion with the knee extended (figure 3(*b*)). Casting was not continued further in these subjects due to the identification of areas of potential tissue breakdown. The time frame for improvement was variable, with some subjects making considerable gains following removal of the first cast, while others exhibited small increases in range with each cast change. Small losses of range were observed at follow-up evaluation (post) compared with the angle achieved after removal of the final cast (end) (figures 3(*a*) and (*b*)).

Data from the pooled analysis are presented in figures 4(*a*) and (*b*) and table 2. Maximal PROM with the knee flexed was considered to represent soleus extensibility, while maximal PROM with the knee extended was considered to represent gastrocnemius extensibility. There was a significant change between the baseline (pre) and final (end) assessment of PROM for both knee flexed and extended conditions ($p < 0.0001$). Median gain in ankle range was 30° (knee flexed) and 15° (knee extended) over the series of casts.

The angles achieved at displacing torques of 5 and 10 Nm

The angles achieved at torques of 5 and 10 N.m were found to be highly correlated ($r^2 = 0.97$), consequently only data for the angle achieved at a displacing torque of 10 Nm are presented (figure 4(*c*), table 2). The median angle achieved when a

Table 2. Median and inter-quartile range values recorded from nine subjects for five measurement occasions associated with the angle casting period

Variable	Pre	Initial	Middle	End	Post	*n*
Maximal PROM (knee flexed) (°)	−10.0 (19.8)	8.0 (17.2)	12.0 (11.2)	20.0 (5.0)	10.0 (9.0)	< 0.0001
Maximal PROM (knee extended) (°)	−5.0 (13.7)	3.0 (13.2)	8.0 (12.7)	10.0 (9.5)	6.0 (10.7)	< 0.0001
Passive torque (angle angle @ 10 N.m)	8.0 (8.7)	5.0 (8.8)	11.0 (10.2)	12.3 (3.1)	14.0 (10.7)	< 0.0001

Median (IQR); PROM = passive range of motion.
Significance determined from Freidman's Rank Test.

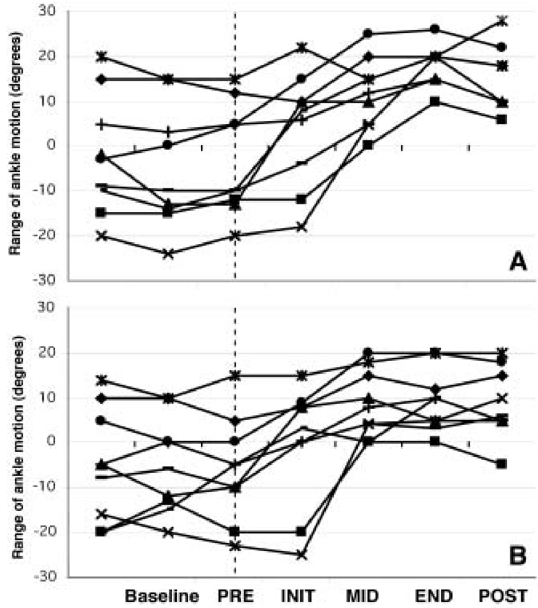

Figure 3. *Repeated goniometric measurement of maximal PROM with the knee flexed (a) or extended (b) shows the progressive improvement over the five test occasions. The first three data points reflect baseline measures, which were taken to determine the stability of ankle range prior to commencement of casting. In some subjects, casting was instigated in response to progressive loss of range, in conjunction with worsening plantarflexor/invertor tonic muscle overactivity.*

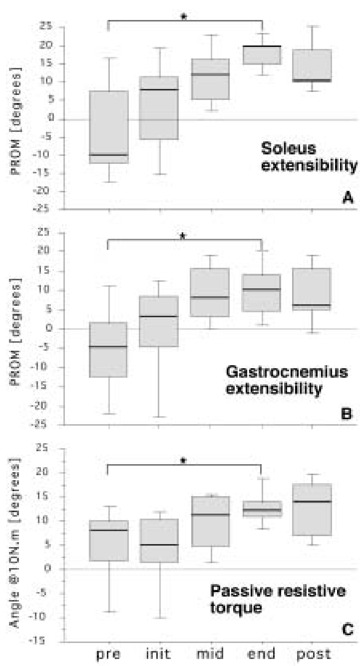

Figure 4. *A significant improvement was demonstrated between the baseline (pre) and final (end) assessment of PROM with the knee flexed (a) ($p < 0.001$), and knee extended (b) ($p < 0.021$). The angle achieved at a displacing torque of 10 N.m also increased significantly over the casted period (c) ($p < 0.0001$).*

displacing torque of 10 N.m was applied increased significantly from 8 to 12.3° DF over the casting period ($p < 0.0001$). There was a decrease of 4° in the median angle following removal of the first cast (initial). Variance in the data was notably less at the end of the casting regime compared with values prior to commencement of casting (figure 4(*c*), table 2).

Stretch induced reflex activity

Electrical activity in the medial soleus muscle in response to stretches at a velocity of $25°.s^{-1}$ demonstrated considerable inter-subject variation. In four subjects, a clearly visible EMG onset occurred in some trials but not in others. Consistent stretch reflexes responses were evident on passive lengthening of soleus muscle in the other four subjects. In these subjects, the onset angle was displaced to the right (that is, further into the available range) over the course of the casting period. Onset angle data from these subjects are presented in figure 5.

Activity during shortening of tibialis anterior muscle was only consistently evident in two subjects. In these subjects, although the amplitude of the EMG exceeded that of the antagonist (soleus), it did not have any impact on the shape of the passive torque-angle curves. In most trials, activity in the tibialis anterior

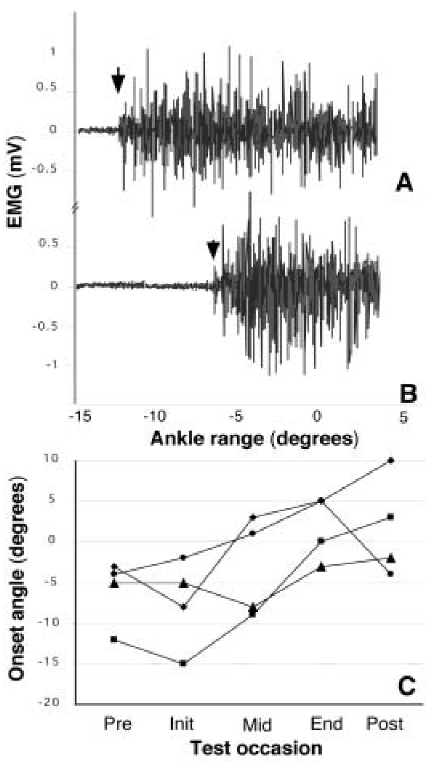

Figure 5. 'Reflex threshold angle' represents the angle of visually detected EMG onset, in response to stretch, in a previously silent soleus muscle. In the illustrative example, the onset angle prior to the casting regime (a) is compared with onset angle following removal of the final cast (b). In the four subjects who demonstrated consistent soleus stretch reflex responses, the trend for reflex threshold angle to move further into the available range is shown (c).

muscle commenced as soon as the footplate began to move. There was no change in the onset angle over the casting period for tibialis anterior activity.

Long term maintenance of increased PROM

A follow-up audit, undertaken at 6 months, in consultation with clinicians involved in the ongoing management of the subjects involved in this study, confirmed that a functional range of ankle mobility was maintained in eight subjects. They were all able to walk short distances, without premature heel-off during terminal stance, although seven were largely wheelchair dependent at this time. The remaining subject, who was unable to stand without maximal assistance, due to extremely limited control of trunk or limb musculature, had regressed to pre-casting levels of ankle deformity.

Discussion

The purpose of this preliminary study was to document the immediate influence of serial casting on muscle extensibility, passive resistive torque and soleus stretch reflex threshold in adults with spastic equinovarus deformity following ABI.

Numerous investigators have reported that serial casting is an effective means of increasing joint range of motion [23, 26–28]. In animal models, an increase in the number of sarcomeres in series in response to maintaining the triceps surae muscles in a lengthened position is well documented [14, 40]. The effect of serial casting on passive torque and stretch reflex responses in adults has not been reported previously, although several studies have examined changes in these parameters in children with cerebral palsy (CP) [30–32]. This study shares the sample size limitation of several previous examinations of the efficacy of serial casting. However, the present data provide further evidence that significant progressive gains in both gastrocnemius and soleus muscle extensibility can be achieved with a serial casting regime of sufficient duration. Follow-up interview at 6 months revealed that the functional range of ankle motion achieved was maintained in all but one individual, despite the fact that the majority of subjects remained only partially ambulant at this time.

Loss of extensibility of the triceps surae muscles, either due to tonic muscle overactivity or resting with the muscles in a shortened position, can be associated with increased muscle stiffness and premature elicitation of stretch reflex activity. In the present investigation, a displacing torque of 10 N.m achieved a greater range of motion at each successive test occasion in all subjects, indicating that reduced resistance to passive stretch resulted from casting, at least in the short term. The angle of onset of stretch induced EMG activity in soleus muscle was also shown to be positively influenced by serial casting, although interpretation of this finding was limited by the small number of subjects with consistent stretch induced responses. It is possible that equipment constraints, which limited the maximal stretch velocity used to $25^\circ.s^{-1}$, may have been the reason that reflex responses were not elicited in some of the subjects studied. Despite this reservation, the present results are similar to outcomes of serial casting reported previously for children with cerebral palsy [30–32].

Brouwer *et al.* [31] examined changes in soleus extensibility, resistance to passive lengthening and 'reflex threshold angle' in seven children with CP following serial casting to increase ankle joint mobility. Casting for 3 weeks resulted in a mean increase in maximal passive range of motion of 12.3° (knee flexed). The method used by these investigators to evaluate resistance to passive lengthening, however, differed considerably from the present study. A spring was attached to the instrumented footplate and the velocity of the dorsiflexion movement resulting from release of the spring was measured. Significant differences in the movement velocity were observed when pre-casting values were compared with results immediately after removal of the third cast and at follow-up 6 weeks later. This finding was considered to represent reduced plantarflexor muscle stiffness. These authors measured 'reflex threshold angle', using software to determine the angle at which EMG activity exceeded a pre-defined background level during the passive stretch and also found a progressive shift of the onset angle into dorsiflexion over the casting period.

In another study involving eight children with CP, statistically significant reductions in reflex induced responses to stretch and the torque required to achieve a plantigrade position were demonstrated after a series of below knee casts were applied (median 5 weeks) [30]. These authors attributed the decrease in stretch sensitivity to lengthening of the series elastic component of the plantarflexor muscles or to an increase in both extrafusal and intrafusal fibre lengths.

These studies provide some support for the suggestion by O'Dwyer *et al.* [20] that increased muscle extensibility is likely to be associated with an apparent reduction in reflex excitability, as stretch reflexes will now be elicited later in the available range. Apart from increased muscle length, there are a number of other mechanisms via which serial casting may achieve relative reduction in stretch reflex excitability. Short duration stretch has been shown to be associated with reduced Hoffman reflex amplitude (considered to represent decreased motor neurone excitability) in normal subjects [41] and individuals with spinal cord injury [42] or spastic hemiplegia [43]. Decreased stretch reflex excitability has also been demonstrated in children with CP following 30 minutes of sustained stretch [44]. Serial casting allows stretch to be applied to the triceps surae muscles for an extended period, which may potentiate the effects observed following short-term stretch. The neurophysiological mechanisms via which sustained stretch produces inhibition of reflex responses are equivocal; however, it has been postulated that auto-inhibition via secondary spindle endings [41, 42] or accommodation of primary spindle endings [18, 44] may be responsible for reduced excitability.

In all of these paediatric casting protocols, the aim of the regime appeared to be to achieve and maintain a plantigrade position of the ankle, *not* to attain greater dorsiflexion range. This practice may have been adopted to prevent adaptive lengthening of the Achilles tendon, which has been demonstrated in immature animals in response to immobilization of the ankle with the plantarflexor muscles under tension [45]. However, predominantly slow twitch muscles, such as soleus, may show profound disuse induced response to this protocol. Case study reports of three children with CP undergoing serial casting to correct equinus gait have demonstrated the consequence of prolonged immobilization in a non-tensioned state [32]. Progressive changes in the muscle characteristics were evidenced by a series of transformations from slow to fast twitch profiles over the casting period, in addition to a reduction in peak twitch force. The investigators suggested that the addition of sarcomeres occurred only while the muscle was under tension and, thereafter, further immobilization in the plantigrade position induced atrophy and a change in the muscle phenotype [32]. In this casting regime, the aim was to increase muscle extensibility and the range of dorsiflexion. These outcomes were expected to result, in part, from myofibrillogenesis, which is stimulated by sustained stretch [46]. Consequently, with the exception of the first cast, which provides a period of familiarization with the experience of immobilization, the triceps surae and adjacent muscles were maintained in a tensioned state. The slight increase in passive resistive torque observed in these subjects after removal of this first cast (figure 4(*c*)) may reflect disuse induced changes in the proportion of connective to muscle tissue [47].

Several elements of this study contribute to the existing body of knowledge concerning evaluation and clinical management of spastic equinovarus deformity, particularly in adults with ABI. Most previous studies have reported only pre- and post-casting goniometric measures, with limited attention to measurement reliability. The use of weekly evaluations allows greater confidence in range of motion outcomes than comparison of single pre-post goniometric measurements. In addition, carefully defined measurement protocols, with known intra-rater error, allowed the identification of small changes in extensibility and passive resistive torque.

Prior to commencement of the study, three criteria were defined for discontinuation of the casting regime. These were: the achievement of 10° of dorsiflexion with the knee extended, no measurable gain of range over three successive cast changes, or the development of areas of pressure or skin breakdown. In three subjects, six or more casts were required to achieve the outcome range of 10° dorsiflexion. Those subjects who required an extended casting regime made very small gains initially. Reference to *a priori* outcome criteria prevented the premature discontinuation of the intervention where gains of range were slower than expected.

The most common rationale for the use of serial casting at the ankle is loss of joint range. However, the sole use of maximal available passive range of motion to determine the need for serial casting to correct equinovarus deformity may be inadequate. The criteria used to define normal ankle range in the literature vary considerably [48]. While there are accepted ranges for functional ankle mobility [39], it is necessary also to consider the amount of force required to achieve that range (i.e. muscle stiffness). As shown in the present study, a significant reduction in muscle stiffness resulted from the casting regime, in conjunction with increased muscle extensibility. At the conclusion of the casting regime, the median angle at 10 N.m was $12.3 \pm 3.1°$. A recent report of passive ankle flexibility suggested that, based on normal population means and standard deviations, the range of ankle dorsiflexion with the knee extended achieved at a stretching torque of 12 Nm would be expected to be between 11.2–25.0° [48]. Thus, taking into account the influence of knee position and the slightly greater displacing force, subjects in the present study could be considered to have changed from 'hypomobile' to 'normal' categories of flexibility, as defined by this substantial normative study (table 2) [48].

It has previously been postulated that a displacing force of 10 N.m approximates the stretching torque applied during clinical evaluation of maximal passive range of motion [49]. In the clinical setting, repeated measurement of the ankle angle achieved at torques between 10–12 N.m, using a standard dynamometer [50] or a customised device [48, 51] has the potential to identify progressive stiffness of the triceps surae muscles. This would allow appropriate intervention to be commenced before functional loss of range occurs. More pro-active use of measures to avoid muscle shortening, especially where triceps surae overactivity is superimposed on prolonged immobility, may reduce the incidence of spastic equinovarus deformity and facilitate functional rehabilitation.

In conclusion, nine out of 10 adult subjects with spastic equinovarus ankle deformity following ABI demonstrated significant improvement in maximal dorsiflexion range, and the angle achieved when a 10 N.m torque was applied, following a serial casting regime. In four individuals with consistent reflex responses to stretches at a velocity of $25^{\circ}.s^{-1}$, a progressive shift of the EMG onset angle further into the available range was recorded coincident with improved mobility.

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