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ORIGINAL ARTICLE

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The effect of electrical stimulation on leg muscle pump activity in spinal cord-injured and able-bodied individuals

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Abstract The purpose of this study was to examine the difference in: (1) effective muscle pump activity (MPA) between voluntary and electrically (ES) induced contractions in able-bodied subjects (ABS); and (2) ES-induced MPA between spinal cord-injured (SCI) individuals and ABS. MPA was measured as relative volume changes in the calf using strain-gauge plethysmography during repeated muscle contractions in the supine position while venous outflow was impeded by a thigh cuff inflated to a range of pressures. Ten SCI individuals and ten ABS participated in this study. ABS showed no significant difference between voluntary and electrically induced MPA [58.1 (18.4)% versus 67.7 (8.7)%, respectively]. SCI individuals showed a significantly lower ES-induced MPA than ABS [21.5 (15.9)% versus 67.7 (8.7)%, respectively]. The low MPA in SCI individuals may be explained by: (1) extensive leg muscle atrophy and/or (2) an "atrophic" vascular system in the legs. The electrical current level seemed to influence MPA (43 mA, 21.5% versus 60 mA, 30.8%) for SCI individuals, whereas no influence of muscle contraction rate on MPA was observed in ABS. The results of this study demonstrate that although ES-induced leg muscle contractions result in adequate MPA in ABS, it leads to significantly less effective MPA in SCI individuals.

Key words Blood redistribution · Paralyzed calf muscles · Paraplegia · Strain gauge plethysmography · Voluntary contractions

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Introduction

In a totally passive upright position, a large proportion of the blood will be pooled in the highly compliant venous system because of the effects of gravity and despite the preventative function of the venous valves (Rowell 1993). If blood pooling persists, arterial blood pressure will be compromised as a consequence of the reduced venous return. An important consequence of this altered cardiovascular function could be orthostatic hypotension with fainting (Rowell 1993).

In the healthy able-bodied subject (ABS), the effects of gravity on blood volume distribution in the upright position can be counteracted by the combined actions of sympathetically mediated vasoconstriction and leg muscle pump activity (MPA). The latter will actively return blood to the heart through compression of the veins by muscle contraction (Folkow et al. 1970; Leyk et al. 1992; Ludbrook 1966; Pollack and Wood 1949; Sheriff et al. 1993a, b; Stegall 1966). In contrast, in spinal cord-injured (SCI) individuals who have lost motor, sensory and autonomic functions below the lesion, neither of these two mechanisms is functional to support blood volume redistribution (Davis 1993; Davis et al. 1990; Hopman 1994; Hopman et al. 1993a, b). As a result, orthostatic intolerance with pre-syncope and/or syncope may occur in these SCI individuals.

It has been speculated that electrical stimulation (ES) of the leg muscles may simulate MPA in SCI individuals and has been used to prevent venous blood pooling in the legs and to increase venous return during exercise (Davis et al. 1990; Glaser 1986; Hooker et al. 1989). When arm exercise alone was compared with the combination of arm exercise and ES of the legs in SCI individuals, the increased cardiac output measured during combined exercise was attributed to facilitation of venous return by leg MPA (Davis et al. 1990; Figoni 1993). Yet, the actual contribution of the muscle pump to blood redistribution in SCI individuals has not been evaluated, and the question remains as to whether the changed circulatory responses found with ES are due to enhanced emptying of leg venous system by MPA, or to an increased active muscle mass and concomitant increase in oxygen demand.

Strain-gauge plethysmography is a simple, non-invasive method for identifying volume changes of the limbs based on vascular activity (Brakkee and Kuiper 1982; Janssen et al. 1996; Pointel et al. 1981). Strain-gauge plethysmography has also been used to assess muscle pump function in healthy individuals (Janssen et al. 1996; Rosfors 1991; Stick et al. 1989; Struckman and Mathiesen 1985) as well as in clinical settings for patients with venous insufficiency (Janssen et al. 1996; Van Gerwen et al. 1992). It has, however, never been used to study MPA during ES of the leg muscles in SCI individuals.

The purpose of this study was to assess the effectiveness of the muscle pump during ES of the calf muscles by means of strain-gauge plethysmography in SCI individuals in comparison with able-bodied controls. To permit an objective evaluation, MPA in able-bodied controls was assessed during voluntary muscle contractions as well.

Methods

Subjects

Ten male SCI individuals and ten healthy male ABS participated in this study. The mean age (SD) of SCI individuals and ABS was 35.1 (8.4) years and 27.0 (2.4) years, respectively. The study was approved by the Faculty Ethics Committee and all subjects gave their written informed consent. The SCI individuals had complete lesions [American Spinal Injury Association (ASIA): A] between T3 and T12. The time of onset of the spinal cord injury ranged from 1 to 18 years [10.1 (5.9) years]. Two SCI individuals and none of the ABS were smokers. None of the subjects had cardiac or peripheral vascular diseases, neither did they use medication that could interfere with the measurements. At least 2 h before the test all subjects refrained from caffeine, alcohol and nicotine to avoid any effect on the vascular tone.

Protocol

The protocol used in this experiment was based on the supine venous pump function test, as used in the Clinical Vascular Laboratory of the University Hospital St. Radboud (Nijmegen, The Netherlands) to assess the degree of venous insufficiency in patients (Janssen et al. 1996). In the test, dorsal flexion and tiptoe movements were rhythmically performed against the pressure produced by inflatable cuffs around the thighs while volume changes were measured by strain-gauge plethysmography. The validity of this supine venous pump function test was established by Janssen et al. (1996), who compared the test with invasive venous pressure measurements as being the gold standard. Comparison of the two methods showed a correlation coefficient of $r = 0.98$ ($P < 0.001$) with a mean difference in pump function of 3.9%.

In this study, SCI individuals and ABS performed the supine venous pump function test, where tiptoe movements (plantar flexion) were performed by either ES (in SCI and ABS) or voluntary contractions (in ABS). In addition to the supine venous pump function test, we also tested venous pump function in an upright position of 70° head-up tilt in order to mimic the real life situations of sitting and standing upright more closely. All subjects lay on a tilt-table with their feet against a foot support. To avoid movements caused by the contractions, the subjects were fixed to the bed using a climbing harness and bandages across their feet and knees. Hip and knees were slightly flexed and supported by foam pads. Prior to the test, the maximal tolerable current level of each ABS was determined. The ES-induced muscle contractions in the SCI individuals were verified visually and by palpation.

To simulate gravity in the supine position, an increased venous pressure was applied using inflatable cuffs around both thighs. Measurements began with inflation of the cuffs to 6.7 kPa or 50 mmHg. This procedure resulted in venous occlusion but did not impede arterial flow. As a result, venous blood volume and venous pressure in the legs of SCI subjects and ABS increased. These volume changes were monitored by plethysmography. When venous pressure equals the pressure in the cuff, and arterial inflow and venous outflow become the same, the volume is stabilized. At this point, with the cuffs still inflated, ES-induced contractions (for both SCI subjects and ABS) or voluntary contractions (VC) for the ABS were made to create MPA and to decrease the blood volume in the legs. In total ten contractions were made and when the volume was stable again, a second series of ten contractions was performed. This procedure was repeated with the cuff inflated at 8.0 kPa (60 mmHg) and 9.3 kPa (70 mmHg). In the ABS group, every first contraction session at each pressure level was induced by ES, whereas every second contraction session consisted of VC (Fig. 1). In the SCI group, both contraction sessions were induced by ES but every first session was induced with the average current (ES_{av}) that had been used in the ABS group (46 mA) and every second session was induced with a current of 60 mA (ES_{60}). The time between the two sessions was determined by the time needed for the plethysmograph signal to return to baseline, in order to allow sufficient recovery between the different sessions.

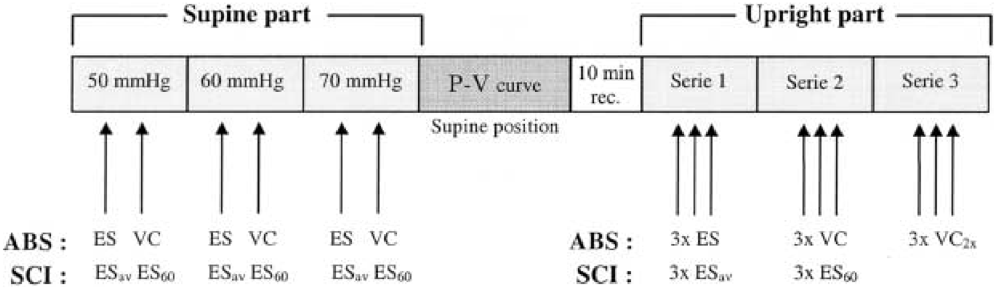

Fig. 1 Muscle pump activity (*MPA*) was determined in the supine position at three pressure levels and in the upright position. The supine and upright parts of the experiment were separated by determining the pressure–volume curve (*P–V* curve). The muscles of able-bodied subjects (*ABS*) were induced to contract electrically (*ES*) and voluntarily (*VC*). Spinal-cord-injured (*SCI*) individuals performed ES-induced contractions with the average current that had been used for ABS (ES_{av}) and with a current of 60 mA (ES_{60}). ABS performed an extra series in the upright position with twice the frequency normally used (VC_{2x}). See Methods for a detailed description of the protocol

After the contraction sessions at the three pressure levels were completed, a pressure–volume curve (*P–V* curve) was determined by measuring the relative volume increase at six different cuff pressures. This *P–V* curve needs to be determined since the relationship between pressure and the volume change is not linear (Brakkee and Kuiper 1982; Pointel et al. 1981). At least six points were measured and the curve was determined by a non-linear logarithmic fit based on the elastic characteristics of the venous vessel wall (Fig. 2). The equation used for the non-linear fit was $\Delta V/V = 1/k \cdot \ln[1 + k \cdot C_0 \cdot (P_v - P_0)]$, where C_0 is the slope of the curve at point $P_0 = P_v$, P_0 is the pressure in the venous system at rest, and k is the coefficient of alinearity, indicating the increase in stiffness with increasing stretch. The r^2 value between data and the model had to be >0.7 to be acceptable for analyses. From this curve the venous capacity at every pressure level could be determined and, secondly, with this curve every volume change at a certain pressure level could be translated to a pressure change induced by the muscle activity – a requirement to calculate MPA.

After completing the *P–V* curve, the upright part of the test was started and the table was tilted to the upright position at an angle of 70°. Because gravity causes the pressure gradient in this situation, the cuffs are no longer needed. When the volume in the legs stabilized again, two series of three contraction sessions were made, with the first three sessions induced by ES (for ABS) or ES_{av} (for SCI) and the second three sessions by VC (for ABS) or ES_{60} (for SCI) (Fig. 1). As shown in Fig. 1, ABS performed a third series of three contraction sessions (VC_{2x}). These voluntary contractions were performed with a contraction frequency that was twice that in the rest of the protocol in order to examine the effect of contraction rate on MPA.

Instrumentation

A two-channel electrical stimulator (Elpha 2000, Danica, Nijkerk, The Netherlands), which was synchronized to provide identical duty cycles for each limb, was used to stimulate the gastrocnemius muscle. Two Bioflex surface electrodes were used for each limb, located on the neuromuscular motor points to create a maximal contraction that was verified both visually and by palpation. Stimulation consisted of biphasic pulses of 200 µs duration at a frequency of 30 Hz. The contraction pattern consisted of 2 s stimulation including 0.5 s of rise-time, followed by a 2-s pause. The pattern lasted for 45 s, which was the time required to get ten full contractions. The first 5 s was used to increase the current to the target value. Every first contraction session of the ABS group was performed with the maximal tolerable current for each individual as defined before the test. Every second session consisted of voluntary contractions with the same magnitude of force and with the same duration as the electrically induced contractions, established by visual and tactile feedback. Every first contraction session of the SCI group was performed with the average current that had been used in the control group. This average current was 46 mA in the supine position and 50 mA in the upright position. Every second session consisted of electrical stimulation with a current of 60 mA.

Measurements

The contraction force was measured using strain gauges at the foot support. The strain gauges were connected to a strain indicator (Type CA660, Peekel Instruments, Rotterdam, The Netherlands) and contraction force was recorded continuously during the test using a Kipp recorder (Kipp and Zonen, The Netherlands).

Strain-gauge plethysmography (Loosco, Amsterdam, The Netherlands) was used to measure relative volume changes in the legs and consisted of two mercury-filled tubes of silicon rubber (SG24/SG33, Medasonics, Calif., USA). The tubes were stretched around the lower leg, 1–2 cm below the origin of the Achilles tendon, which is about 10 cm above the lateral malleolus. This placement is chosen in order to reduce the noise that can occur because of the contractions and, therefore, to obtain the best prediction of MPA (Janssen et al. 1996).

Data analysis

In order to calculate MPA a *P–V* curve was determined by measuring the relative volume increase at six different cuff pressures. When these volume changes are plotted against the different cuff pressures, the *P–V* relationship is found for the strain-gauge location that is used (Fig. 2). When the *P–V* curve is known, the volume reduction during exercise can be converted to a pressure decrease. The initial pressure (P_1) is the cuff pressure. According to the *P–V* curve, V_1 is the volume associated with pressure P_1. The volume expelled because of the exercise was measured by plethysmography and is reflected by V_2. According to the *P–V* relationship, V_2 corresponds to pressure P_2 and the pressure decrease that is established by the exercise can be calculated from the difference

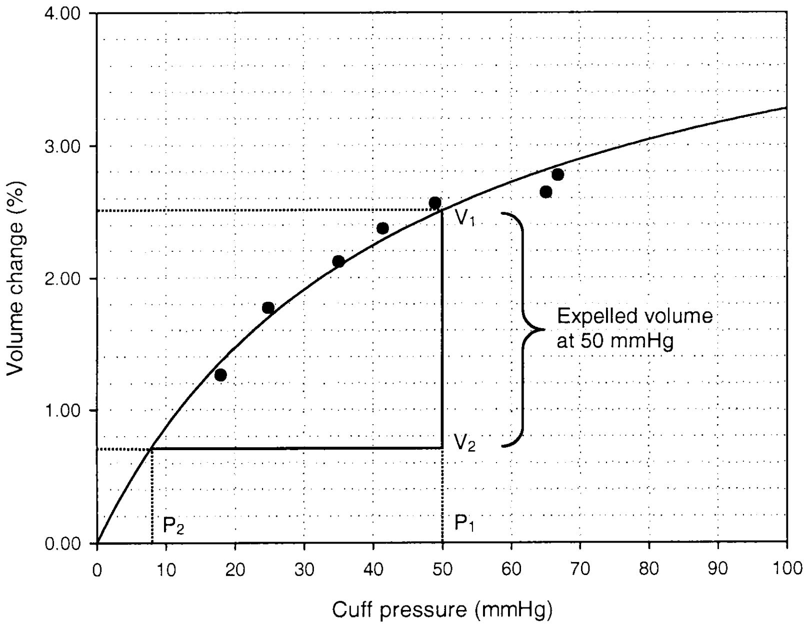

Fig. 2 Determination of the pressure-volume curve (*P–V* curve) for a healthy subject. The measured volume increase (%) is plotted against the different cuff pressures (mmHg). P_1 is the initial pressure at which the exercise was performed. V_1 is the volume increase associated with P_1. The expelled volume during calf muscle exercise is reflected by the difference between V_1 and the volume immediately after exercise (V_2). According to the curve, V_2 corresponds to the pressure P_2. From the pressure caused by exercise (P_1–P_2) and expressed as a percentage of the initial pressure, muscle pump activity (*MPA*) can be calculated as $\mathrm{MPA}(\%) = (P_1 - P_2)/P_1 \cdot 100\%$

between P_1 and P_2 (P_1–P_2). Muscle pump activity is expressed as a percentage of the initial pressure and can be calculated at a certain pressure level as $\mathrm{MPA}(\%) = (P_1 - P_2)/P_1 \cdot 100\%$. MPA for the supine test was than calculated as the mean value attained from the three pressure levels (50, 60, 70 mmHg or 6.7, 8.0 and 9.3 kPa). This way, a MPA value was calculated for $\mathrm{ES_{av}}$, $\mathrm{ES_{60}}$, ES and VC. For the upright test, the only pressure level is the hydrostatic pressure, determined by the height of the subject. MPA was calculated as the mean volume reduction attained from the three contraction sessions in one series. An MPA value was calculated for $\mathrm{ES_{av}}$, $\mathrm{ES_{60}}$, ES, VC and VC_{2x}.

Statistical analysis

A Student's t-test was applied to determine differences in the physical characteristics and ES-induced MPA of SCI subjects and ABS. A paired Student's t-test was applied to determine differences in MPA between VC and ES-induced contractions, between the supine and upright positions, between the different current levels and between the different contraction rates. To protect against a type-I error, an alpha of 0.01 was chosen. A Pearson correlation coefficient was calculated for SCI subjects between MPA and muscle force, calf circumference, lesion level, time of existence of the lesion and the appearance of spasms. All results are reported as mean (standard error). $P < 0.05$ was considered statistically significant.

Results

The physical characteristics of the subjects are shown in Table 1. SCI subjects were significantly older than ABS, and had a significantly smaller calf circumference. The SCI and ABS groups both played sport for the same number of hours per week.

The P–V curve revealed a significant difference in venous capacity, which was 50% lower in the SCI subjects compared with ABS. The force production was measured in ten ABS and eight SCI individuals and is shown in Fig. 3. The mean force achieved by SCI subjects [30.1 (45.9) N] during $\mathrm{ES_{av}}$ was significantly lower than the force achieved by ABS following ES [384.0 (72.2) N], both in the supine position.

The MPA of ABS was the same whether contractions were voluntary or induced electrically, for both the supine and the upright positions (Fig. 4). MPA in the supine position was 58.1 (18.4)% during VC and 67.7 (8.7)% during ES-induced contractions. In the upright position MPA was 49.9 (15.5)% and 51.8 (15.8)%, for VC and ES, respectively.

Table 1 Physical characteristics [mean (SD)] of SCI and ABS. (*N.S.* No significant difference, *Sign.* significant difference)

	SCI		ABS		P-value
	Mean	SD	Mean	SD	
Height (cm)	182.6	6.1	185.7	6.9	N.S.
Mass (kg)	77.9	13.0	79.8	7.7	N.S.
Age (years)	35.1	8.4	27.0	2.4	Sign.
Calf circumference (cm)	32.2	2.7	38.6	1.7	Sign.
Weekly sport (h)	3.7	3.9	4.0	2.2	N.S.
Time since onset of SCI (year)	10.1	5.9			

$P < 0.05$ was considered statistically significant

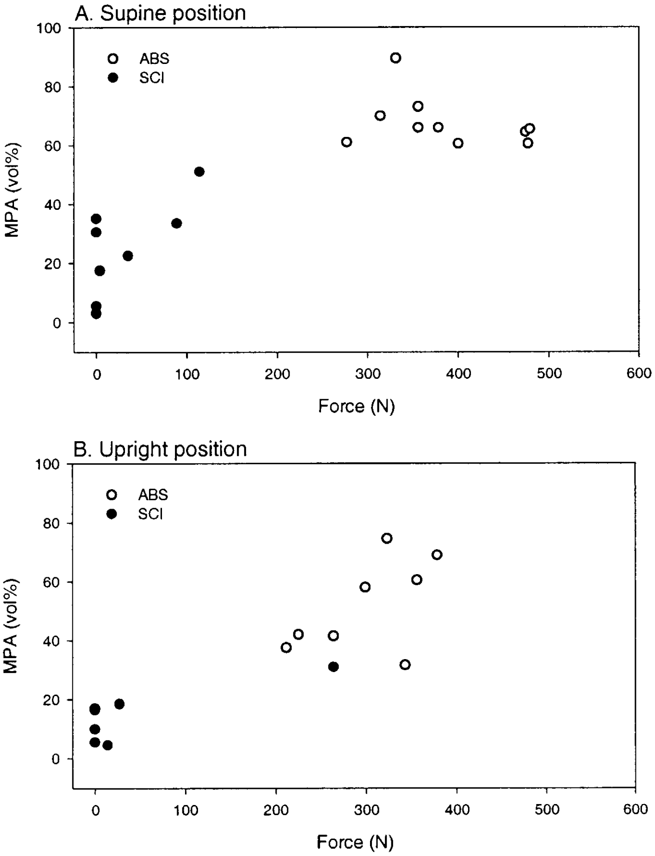

Fig. 3 Muscle pump activity (*MPA*) versus force production in the supine (**A**) and upright (**B**) positions as a result of electrical stimulation (*ES*) in able-bodied subjects (*ABS*; ○) and spinal cord-injured (*SCI*; ●) individuals. In SCI, electrical stimulation was carried out using the average current (ES_{av}) used for ABS. No correlation between MPA and force production was found within each group

SCI subjects had a significantly lower MPA ($P < 0.001$) compared with ABS in both the supine and the upright position when using ES at the same current level (Fig. 5). In the supine position, SCI had an MPA of 21.5 (15.9)% while ABS had an MPA of 67.7 (8.7)%. In the upright position, MPA was 13.4 (9.1)% and 51.8 (15.8)%, for SCI and ABS, respectively. Although the MPA in SCI subjects was significantly higher using the high current level in the supine position [30.8 (18.7)% versus 21.5 (15.9)%], it still remained significantly lower than in ABS [67.7 (8.7)%].

Concerning the influence of position, it was found that ABS had significantly lower ES-induced MPA in the upright position compared with the supine position [51.8 (15.8)% and 67.7 (8.7)%, respectively], while no difference was found when the contractions were voluntary. SCI subjects also had a significantly lower MPA in the upright position compared with the supine position during $\mathrm{ES_{60}}$ [14.7 (12.4)% and 30.8 (18.7)%, respectively] while no difference was found during $\mathrm{ES_{av}}$.

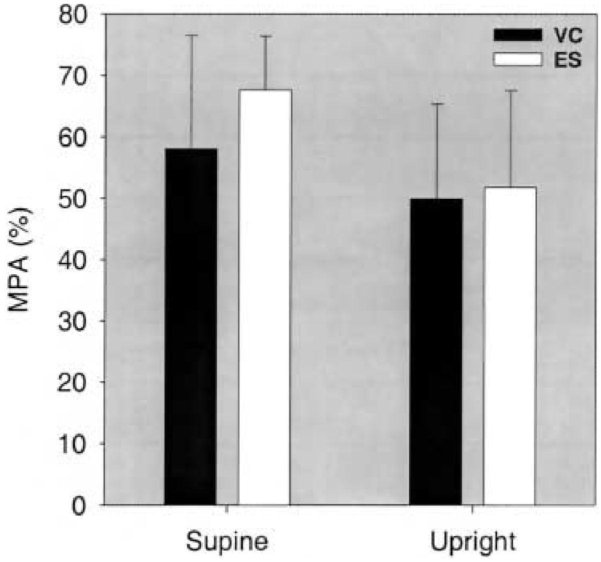

Fig. 4 Muscle pump activity (*MPA*) in controls (*ABS*) as a result of electrically induced contractions (*ES*) and voluntary contractions (*VC*) in the supine and upright positions

The increased muscle contraction rate, as achieved by ABS in the third contraction session in the upright position, had no significant effect on MPA.

A significant correlation ($P < 0.02$) between MPA and the venous capacity and between MPA and calf circumference was found for the total group of participants. Although a significant correlation ($P < 0.02$) between MPA and muscle force was found in the total group, no correlation between MPA and muscle force was found within each group (Fig. 3). No correlation was observed between MPA and lesion level, between MPA and the duration of the spinal cord injury, or between MPA and the appearance of spasms in the SCI subjects.

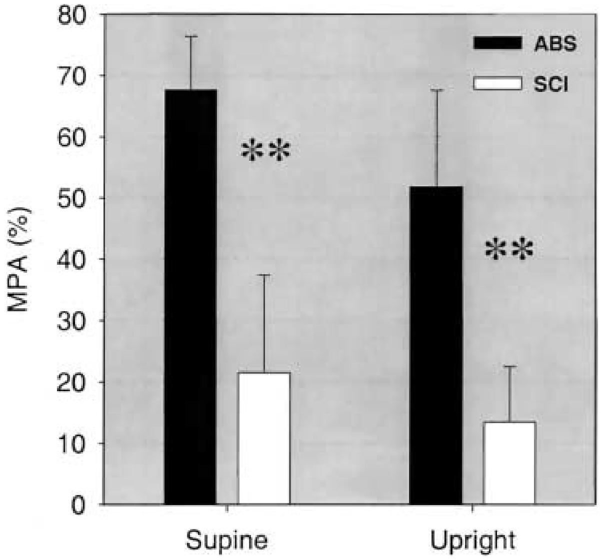

Fig. 5 Muscle pump activity (*MPA*) in the supine and upright positions as a result of electrical stimulation (*ES*) in able-bodied subjects (*ABS*) and spinal-cord-injured (*SCI*) individuals. **Significant differences ($P < 0.01$) between the groups

Discussion

In healthy individuals MPA during voluntary contractions has been assessed accurately using plethysmography (Rosfors 1991; Stick et al. 1989; Struckman and Mathiesen 1985). To our knowledge, it has never been verified whether artificial stimulation of the leg muscles can simulate MPA. This, however, could be highly important for SCI individuals who depend on ES for leg muscle contractions.

This study shows that in ABS approximately 60% of the blood volume increase, caused by venous occlusion or adopting an upright posture, is expelled from the muscles when they are contracted voluntarily or following electrical stimulation. It is notable that no difference in MPA was found between voluntary and ES-induced contractions, indicating that ES of the calf muscles is able to simulate MPA. The results for the ABS in this study are slightly less than the normal values reported by Janssen et al. (1996) and by Van Gerwen et al. (1992). This may be explained by the different positions of the legs in these studies. In the Janssen et al. (1996) and Van Gerwen et al. (1992) studies, the subjects' knees were bent at an angle of 120° to be completely free from the bed and to prevent compression of the veins. In contrast, we were forced (to make the results of both groups comparable) to position our subjects with their hip and knees only slightly flexed and supported by a foam pad under their thighs and upper legs. Furthermore we had to use bandages across their feet and knees to prevent movements caused by spasms. Therefore, it seems reasonable to assume that these restrictions in position caused a minor obstruction in the superficial venous system, and have led to the slightly lower MPA in both controls and SCI compared to the aforecited studies.

SCI individuals had a significantly lower MPA compared with ABS. This indicates that although ES of the calf muscles can simulate MPA, it induces significantly less effective MPA in SCI individuals. This may be explained by the following two hypotheses: (1) muscle atrophy of the leg muscles in SCI individuals may result in inadequate compression of the veins and, therefore, a less effective MPA; and (2) the fact that SCI individuals have less blood stored in their legs in response to venous occlusion and adopting an upright posture compared to ABS. The first hypothesis is supported by the observations that SCI have a significantly lower calf circumference than ABS and dramatically reduced muscle strength in response to contractions induced electrically (10% of the force production of ABS). These observations agree with previously reported results (Figoni 1993; Glaser 1986). However, the effect of decreased force production on MPA is not a clear-cut issue. Several studies indicate that mild contractions are nearly as effective as forceful muscle contractions at mobilizing blood (Flamm et al. 1990; Ludbrook 1966; Sheriff et al. 1993b; Wang et al. 1960). This is confirmed by the findings of the present study: (1) a lack of correlation between force production and MPA within each group; and (2) markedly different levels of MPA in four SCI individuals with no detectable force production (Fig. 3). However, the greatly reduced force production by SCI individuals may play a role in their poor MPA.

The second hypothesis accords with the results of Hopman et al. (1994), who found a decrease in venous capacity in SCI individuals compared to ABS using venous occlusion plethysmography. This was confirmed in the present study: venous capacity was 50% lower in SCI individuals compared with ABS. Venous capacity is apparently reduced because the vascular bed is diminished as a result of inactivity and disuse of the muscles in the paralysed part of the body (Hopman et al. 1996). Thus, the leg muscle contractions induced by ES are not able to remove a substantial part of the blood volume from the legs simply because the existing blood volume in the legs is too small. Consistent with this explanation is the report by Knutsson et al. (1973), who found that SCI individuals have a reduced total blood volume.

Changing the stimulation frequency [low (2 s on/2 s off) and high (1 s on/1 s off)] did not affect the MPA of ABS. This contrasts with the work of Sheriff et al. (1993a), who measured an immediate rise in the vascular conductance (used as an indication of muscle pump function) of the dog hindlimb after doubling the speed of the treadmill from 3.2 km/h (2 mph) to 6.4 km/h (4 mph). This is probably associated with an increase in contraction strength as well as the contraction rate. However, differences in the methods and species used, i.e., dogs versus humans, make it hard to compare MPA between the two studies.

The higher current level, 60 mA, that was used for SCI individuals resulted in a significantly higher MPA as compared to the average current level, which may be because a larger muscle mass was activated. However, the MPA was still not as effective (30.8%) as the normal value of 60% in healthy individuals. Moreover, when treated with the same current level (46 mA), SCI and ABS produced markedly different MPA. We, therefore, doubt that higher current levels can improve MPA up to normal levels in SCI individuals.

In conclusion, this study demonstrates that simulating the muscle pump by electrically stimulating the leg muscles is possible in ABS but leads to a significantly less effective MPA in paraplegic individuals. This may be explained by the muscle atrophy and low venous capacity in paraplegic individuals.

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