Venous emptying from the foot: influences of weight bearing, toe curls, electrical stimulation, passive compression, and posture

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Broderick BJ, Corley GJ, Quondamatteo F, Breen PP, Serrador J, OLaighin G. Venous emptying from the foot: influences of weight bearing, toe curls, electrical stimulation, passive compression, and posture. J Appl Physiol 109: 1045–1052, 2010. First published August 12, 2010; doi:10.1152/japplphysiol.00231.2010.—This study investigated the hemodynamic properties of the plantar venous plexus (PVP), a peripheral venous pump in the human foot, with Doppler ultrasound. We investigated how different ways of introducing mechanical changes vary in effectiveness of displacing blood volume from the PVP. The contribution of the PVP was analyzed during both natural and device-elicited compressions. Natural compressions consisted of weight bearing on the foot and toe curl exercises. Device-elicited compressions consisted of intermittent pneumatic compression (IPC) of the foot and electrically elicited muscle contractions. Ten healthy participants had their posterior tibial, peroneal, anterior tibial, and popliteal vein blood flow monitored while performing these natural and device-elicited compressions of the PVP supine and in an upright position. Results indicated that 1) natural compression of the PVP, weight bearing and toe curls, expelled a significantly larger volume of blood than device-elicited PVP compression, IPC and electrical stimulation; 2) there was no difference between the venous volume elicited by weight bearing and by toe curls; 3) expelled venous volume recorded at the popliteal vein under all test conditions was significantly greater than that recorded from the posterior tibial and peroneal veins; 4) there was no significant difference between the volume in the posterior tibial and peroneal veins; 5) ejected venous volume recorded in the upright position was significantly higher than that recorded in the supine position. Our study shows that weight bearing and toe curls make similar contributions to venous emptying of the foot.

The plantar venous plexus; peripheral venous pump; neuromuscular electrical stimulation; intermittent pneumatic compression; deep vein thrombosis

The plantar venous plexus (PVP) is a venous pumping structure located in the plantar aspect of the foot. The plexus is made up of the lateral plantar vein, medial plantar vein, and deep plantar venous arch as well as a complex system of deep interconnections between the medial and lateral plantar vein (Fig. 1) (6). The description of the PVP by Gardner and Fox in 1983 (11) highlighted the importance of the foot in lower limb venous hemodynamics. Gardner and Fox found, using videophlebography, that the deep plantar veins emptied immediately on weight bearing but toe and ankle contractions failed to significantly empty the veins. The authors reached the conclusion that venous outflow from the foot operates primarily as a result of the longitudinal stretching of the deep plantar veins due to the extension of the tarsal arch and tarso-metatarsal joints on weight bearing. This finding is the principle on which several modern intermittent pneumatic compression (IPC) devices operate. Foot IPC devices imitate weight bearing through passive compression of the PVP via a rapidly inflating and deflating cuff surrounding the foot. These devices have had a significant impact on the prevention of postoperative deep vein thrombosis (DVT) and the reduction of posttraumatic swelling and pain (10, 16–19, 21).

However, some controversy still exists over the precise physiology of the venous foot pump. Binnas and Pho (3) have suggested, after a study of 14 cadaveric feet, that compression of the foot pump via weight bearing, as described by Gardner and Fox (11), was probably due to the contraction of the intrinsic muscles of the foot. The authors speculated that electrical stimulation of these muscles may be more effective at activating the venous pump and emptying the PVP than IPC (11). However, neither study involved hemodynamic measurements, so the relative contribution of weight bearing versus voluntary contraction of the intrinsic muscles of the foot to venous blood flow remained unclear.

The aim of our work was to contribute to a more complete understanding of the venous foot pump and of its contribution to lower extremity venous hemodynamics. To this end, this paper describes a hemodynamic study of the healthy human foot during voluntary weight bearing, during voluntary toe curl exercises, while undergoing foot IPC, and with application of neuromuscular electrical stimulation (NMES) to the intrinsic muscles of the foot. Doppler blood flow measurements were used to identify the dominant physiological mechanism for promoting venous return from the foot.

METHODS

Ten healthy volunteers (5 men, 5 women) participated in this study. Participants had median height of 1.7 m (range: 1.6–1.9 m), mass of 68.4 kg (56.1–81.4 kg), and body mass index of 22.1 kg/m² (21–26.4 kg/m²). Subjects reported no history of cardiac, respiratory, neurological, vascular, or dermatologic problems. Ethical approval for this study was granted by the National University of Ireland Galway Research Ethics Committee, and all participants provided written informed consent. Each volunteer participated in four separate test conditions that were designed to assess the physiological mechanism of the plantar venous pump while standing and supine: 1) voluntary weight bearing, 2) voluntary toe curl exercises, 3) IPC of the foot, and 4) NMES of the intrinsic foot muscles.
muscles.

ankle joint as still as possible to reduce cocontraction of the calf held the contraction for 3 s. Participants were instructed to keep their flexed the toes of his or her right foot as forcefully as possible and pants distributing their weight evenly on both legs. The participant movement was recorded by Doppler ultrasound.

screen placed next to the participant allowed them to monitor the own body weight on their right leg measured by a force transducer. A table. Subjects used the hand grips to exert a force equivalent to their tested in random order. To examine the effect of the hydrostatic gradient on PVP filling, all test conditions were performed with the participant both in a standing position and while lying supine on an examination table. The examination table used in this study had an attached footplate and handle-grips. The test conditions are illustrated in Fig. 3. Resting hemodynamics were recorded before implementa-
tion. The veins of interest were the deep veins of the leg, namely, the posterior tibial, peroneal, anterior tibial, and popliteal veins (Fig. 2). Testing of each condition under investigation began by determining resting venous flow followed by three repetitions of the condition under test. Participants rested for at least 20 s between each repetition to allow for venous refilling. Three seconds was chosen as the maximum stimulation duration to ensure that all test conditions were within the same comparable time frame. All four conditions were tested in random order. To examine the effect of the hydrostatic influence of the leg muscles as relaxed as possible and their knee joint in full extension. The elicited venous blood flow pulse was measured. Weight was then shifted back over to the left leg.

The participants imitated weight bearing on the foot while supine by holding two handle-grips mounted on the side of the examination table. Subjects used the hand grips to exert a force equivalent to their own body weight on their right leg measured by a force transducer. A screen placed next to the participant allowed them to monitor the exerted force. The surge in venous blood flow elicited from the movement was recorded by Doppler ultrasound.

To perform toe curls in the supine position, an 8-cm-thick piece of foam was placed under the thigh and ankle. This was necessary to prevent the pressure applied to the soleus muscle due to the leg’s resting position on the bed from closing the posterior tibial and peroneal veins, which would otherwise disrupt the blood flow.

NMES. Surface NMES is the application of an electrical stimulus to motor points in the body with electrodes placed on the surface of the skin to elicit a muscular contraction. NMES was used to stimulate the plantar muscles of the foot. Two neurostimulation PALS hypoallergenic skin surface electrodes (Nidd Valley Medical) were used. The active electrode (5 cm × 5 cm) was placed over the posterior tibial nerve, between the Achilles tendon and the medial malleolus. The reference electrode (5 cm × 10 cm) was placed across the metatarsal heads on the sole of the foot in order to stimulate as many plantar muscles as possible (Fig. 4B). The participant was given time to become familiar with the sensation of stimulation with a series of self-administered test stimuli. During this initial setup period, the electrode positioning was slightly adjusted if necessary to achieve a visible flexion of the toes. The subjects were asked to increase the stimulation intensity gradually to their highest tolerable stimulation intensity. For NMES testing, during standing and while supine, the participant adopted a position similar to that used during toe curl testing.

NMES was applied with the Duo-STIM muscle stimulator (4). The stimulator was programmed to provide a pulse width of 350 µs, an interpulse interval of 100 µs, a frequency of 36 Hz, a delay time of 20 s, a ramp-up time of 500 ms, a contraction time of 1 s, and a ramp-down time of 500 ms. The stimulation parameters were selected to achieve maximum blood flow while ensuring subject comfort and are based on the stimulation guidelines described by Baker et al. (2).

Intermittent pneumatic compression. The inflation pads were placed on the participant’s right foot (Fig. 4A). The system performed three test compressions before any measurements were taken. The
same standing and supine positions adopted for toe curls were also used here.

IPC was applied with the Novamedix AV Impulse System 6000. The system was set to inflate the foot compression pads every 20 s with a 3-s total inflation time and a 200-mmHg inflation pressure.

**Duplex Scanning**

Duplex ultrasound (GE LOGIQ e) was performed with a 4- to 8-MHz linear transducer. The Doppler waveform was recorded in response to a single compression of the PVP. The venous hemodynamic parameters studied were peak venous velocity (cm/s), intensity-weighted mean velocity (cm/s), and blood vessel cross-sectional area (cm²). Intensity-weighted mean velocity represents a mean velocity averaged over the entire cross section of the blood vessel (15). At least three different measurements were performed, and the average was used for analysis. The ejected venous volume (ml) from the PVP in response to a single compression was calculated as cross-sectional area (cm²) × mean velocity (cm/s) × total duration (s). Cross-sectional area was measured by recording the diameter of the vessel from the B-mode video capture at each repetition of each maneuver just before the onset of blood flow. Flow elicited due to a single compression of the PVP lasted no longer than 4 s; therefore, this was set as the total duration. To acquire resting hemodynamic data, 4 s of flow was recorded once the participant was resting comfortably in a steady position. Ejected venous volume was the primary outcome measure of this study. Examples of the Doppler waveforms recorded in response to the standing test conditions are shown in Fig. 5.

Three measurement sites were chosen for this study (Fig. 2). The first measurement site was approximately one-third of the way up the medial shank, between the tibia and the soleus muscle. This site allowed for imaging of the posterior tibial vein and the peroneal vein (Fig. 2). The second site was halfway up the lateral shank, between the tibia and the lateral head of the gastrocnemius muscle in order to image the anterior tibial vein. The posterior tibial vein was chosen to quantify the local volume of blood expelled from the PVP, because the veins that comprise the PVP primarily drain into the posterior tibial vein (20). The posterior tibial vein is doubled. From the point of view of the observation point (i.e., the Doppler ultrasound probe), it was possible to recognize a more superficial vessel and a deeper one parallel to it, both belonging to the posterior tibial vein. Previous observations would suggest that the more superficial vein originates from the medial plantar vein whereas the deeper vein originates from the lateral plantar vein (6). As a result, each of these two parts of the posterior tibial vein was measured separately. Since it was consistently found that one strand of the posterior tibial vein was deeper than the other, we refer to one strand as the deep strand of the posterior tibial vein and to the other as the superficial strand. The same convention is used for the anterior tibial vein. The peroneal vein drains the area surrounding the calcaneus and merges proximally with the posterior tibial vein (8). The dorsal veins of the foot drain into the anterior tibial vein, which merges with the posterior tibial vein to become the popliteal vein before the knee. Consequently, the third measurement site, the lateral aspect of the knee in the popliteal fossa, was chosen to image the popliteal vein in order to determine the overall effect that each test condition has on lower limb blood flow.

All Doppler measurements were recorded by a single investigator. Intraindividual reliability analysis was carried out on the mean velocity measurements taken from 48 sets of 3 repeated IPC compressions.

**Statistical Analysis**

A repeated-measures ANOVA was used to determine the effect of each test condition on blood flow (SPSS). Any violations of the...
The assumption of sphericity were corrected with the Huynh-Feldt correction for estimates of sphericity >0.75 or the Greenhouse-Geisser correction for estimates <0.75 (12). A priori contrasts were performed on all maneuvers to test for differences with respect to resting. A least significant difference correction was applied to any post hoc analysis to correct for multiple comparisons. Blood flow data were nonnormal, and therefore pairwise comparisons between maneuvers performed in the upright and supine positions were analyzed by Wilcoxon’s signed-rank test. Doppler ultrasound operator consistency was determined with Cronbach’s $\alpha$ (7). In all analyses, a $P$ value of <0.05 was considered statistically significant.

RESULTS

The Cronbach $\alpha$ value for the repeated IPC Doppler measurements was 0.982. Results for each vessel studied are summarized in Table 1. The four graphs of Fig. 6 show the volume of blood expelled under each test condition in the standing and supine positions for the superficial and deep strands of the posterior tibial vein, peroneal vein, and popliteal vein.

Upright Position

Repeated-measures ANOVA revealed that blood flow volume varied significantly with test condition in the upright position ($P < 0.01$). The highest ejected volume in all of the veins was produced with weight bearing ($P < 0.01$) and toe curls ($P < 0.05$); however, no significant difference was observed between weight bearing and toe curls ($P = 0.592$) (Table 1). The lowest ejected volume in all veins was produced with NMES, which was not significantly different from resting ($P = 0.667$).

Ejected venous volume was highest through the popliteal vein ($P < 0.001$) and was ~12 times higher than the next-largest vein’s expelled volume (peroneal vein). There were no differences in volume among the superficial strand of posterior tibial vein, the deep strand of the posterior tibial vein, and the peroneal vein. Weight bearing and toe curls produced an almost fivefold increase in volume compared with resting in the popliteal vein. However, the same maneuvers produced over a 10-fold increase in volume compared with resting in the superficial and deep posterior tibial vein strands and peroneal vein ($P < 0.05$ for all conditions). There were no influences of sex on upright ejected venous volume ($P = 0.208$).

Supine Position

Test conditions also had a significant effect on the volume of blood expelled in the supine position ($P < 0.01$), with the highest volume expelled across all veins produced again by weight bearing ($P < 0.01$) and toe curls ($P < 0.05$). As in the

Table 1. Venous volume ejected from the foot in response to voluntary and involuntary methods of activating the plantar venous plexus

<table>
<thead>
<tr>
<th>Vein</th>
<th>Weight bearing</th>
<th>Toe curls</th>
<th>IPC</th>
<th>NMES</th>
<th>Resting</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standing Position</strong></td>
<td></td>
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<tr>
<td>Posterior tibial (superficial strand)</td>
<td>1.22 (1.07–1.95)</td>
<td>0.65 (0.4–1.53)</td>
<td>0.48 (0.35–1.36)</td>
<td>0.21 (0.1–0.33)</td>
<td>0.09 (0.04–0.13)</td>
</tr>
<tr>
<td>Posterior tibial (deep strand)</td>
<td>1.31 (0.96–2.45)</td>
<td>0.9 (0.57–1.78)</td>
<td>0.77 (0.4–1.14)</td>
<td>0.24 (0.13–0.77)</td>
<td>0.09 (0.05–0.14)</td>
</tr>
<tr>
<td>Peroneal</td>
<td>2.92 (1.47–3.91)</td>
<td>2.96 (1.93–4.42)</td>
<td>0.48 (0.3–0.84)</td>
<td>0.25 (0.17–0.46)</td>
<td>0.18 (0.14–0.21)</td>
</tr>
<tr>
<td>Popliteal</td>
<td>33.34 (18.17–43.4)</td>
<td>31.04 (17.74–30.93)</td>
<td>9.08 (6.44–10.56)</td>
<td>7 (4.35–8.82)</td>
<td>7.09 (5.84–7.85)</td>
</tr>
<tr>
<td>Anterior tibial (superficial strand)</td>
<td>0.37 (0.26–0.55)</td>
<td>0.36 (0.17–0.58)</td>
<td>0.22 (0.12–0.57)</td>
<td>0.11 (0.06–0.2)</td>
<td>0.1 (0.03–0.18)</td>
</tr>
<tr>
<td>Anterior tibial (deep strand)</td>
<td>0.26 (0.37)</td>
<td>0.16 (0.03–0.37)</td>
<td>0.23 (0.04–0.32)</td>
<td>0.19 (0.02–0.29)</td>
<td>0.08 (0.02–0.12)</td>
</tr>
<tr>
<td><strong>Supine Position</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Posterior tibial (superficial strand)</td>
<td>0.4 (0.3–1.06)</td>
<td>0.78 (0.19–0.84)</td>
<td>0.34 (0.19–0.5)</td>
<td>0.08 (0.04–0.28)</td>
<td>0.12 (0.09–0.13)</td>
</tr>
<tr>
<td>Posterior tibial (deep strand)</td>
<td>1.5 (0.58–1.9)</td>
<td>0.49 (0.43–0.73)</td>
<td>0.46 (0.31–0.57)</td>
<td>0.15 (0.04–0.35)</td>
<td>0.03 (0.02–0.13)</td>
</tr>
<tr>
<td>Peroneal</td>
<td>0.88 (0.39–1.81)</td>
<td>1.01 (0.69–1.32)</td>
<td>0.14 (0.08–0.39)</td>
<td>0.18 (0.09–0.51)</td>
<td>0.07 (0.03–0.09)</td>
</tr>
<tr>
<td>Popliteal</td>
<td>14.88 (9.92–18.99)</td>
<td>17.04 (9.65–20.77)</td>
<td>6.78 (4.79–7.01)</td>
<td>5.64 (3.53–7.6)</td>
<td>5.41 (3.91–7.03)</td>
</tr>
</tbody>
</table>

Values (in ml) are expressed as medians (interquartile range). IPC, intermittent pneumatic compression; NMES, neuromuscular electrical stimulation.
upright position, no significant difference was observed between supine weight bearing and toe curls ($P = 0.591$) (Table 1). NMES again produced the lowest ejected volume, which was not different from resting ($P = 0.219$).

Ejected venous volume again was highest through the popliteal vein ($P < 0.001$), which was over 15 times higher than the peroneal vein’s ejected volume. Volume of expelled blood in the superficial and deep strands of the posterior tibial vein and the peroneal vein were not different from each other. Similar to the upright position, both strands of the posterior tibial vein and the peroneal vein experienced an over 10-fold increase in volume due to the maneuvers compared with resting, which was significantly larger than the increase observed in the popliteal vein ($P < 0.05$ for all conditions). There were no influences of sex on supine expelled venous volume ($P = 0.161$).

**Effect of Position—Hydrostatic Gradient**

Overall, ejected venous volume in the upright position was $\sim 78\%$ higher than in the supine position ($P < 0.05$). The differences were in the weight bearing, toe curl, and IPC interventions. There was no difference between the supine and standing resting volumes in either position for any vein. There was a significant difference in vessel diameter between standing and supine positions ($P < 0.001$). On average vessel diameter was $\sim 25\%$ larger in the standing compared with supine position.

**Anterior Tibial Vein**

Figure 7 shows the ejected venous volume through the superficial and deep strands of the anterior tibial vein. It was not possible to obtain a complete Doppler measurement set from the anterior tibial vein. The data set contained $n = 6$ samples and consisted of upright measurements only. As a consequence, the anterior tibial data could not be reported as part of the main repeated-measures ANOVA and therefore were analyzed separately. Voluntary and involuntary PVP compression had no significant effect on the ejected venous volume through the anterior tibial vein ($P = 0.077$). There were no significant differences between the expelled volume in the superficial and deep strands of the anterior tibial vein ($P = 0.539$).

**DISCUSSION**

The PVP is a structure located in the plantar aspect of the foot that plays an important role in lower limb hemodynamics. Its physiological mechanism for expelling blood depends on external forces acting to collapse the compliant elements of the plexus. We investigated the effects of two methods of expelling blood from the PVP: natural compressions that consisted...
of weight bearing on the foot, a toe curl exercise and device-elicited compressions through the use of IPC of the foot and NMES of the intrinsic muscles of the foot. The results demonstrate five main findings: 1) weight bearing and toe curls expelled a significantly larger volume of blood than expelled by IPC and NMES; 2) there was no significant difference in the volume of blood elicited by weight bearing and toe curl exercises; 3) ejected venous volume recorded at the popliteal vein under all test conditions was significantly greater than that recorded from the posterior tibial and peroneal veins; 4) there were no significant differences between the ejected volume in these distal veins; 5) change in posture has a significant effect on the volume of blood ejected.

The ejected volume was calculated based on the diameter of the veins measured just before the onset of blood flow. In the setting used, because of technical limitations, any potential diameter changes occurring during the course of the maneuvers could not be taken in account. This is particularly true for weight bearing and toe curls because these maneuvers inherently involved cocontractions of the calf muscles that may have dynamically changed the diameter of the vessel. Therefore, we subsequently quantified likely changes in vein diameter possibly occurring during these maneuvers. To this end, we undertook additional measurements on five subjects comparable to the study cohort. Participants underwent a B-mode ultrasound examination of the largest and smallest vessels examined in the study (the popliteal vein and the strand of the posterior tibial vein that was best visualized). We recorded the real-time video output from the ultrasound machine with a video-capture system while imaging these vessels in the transverse plane. A custom MATLAB program was designed to read the recorded ultrasound video and to track the diameter of the vessel as the subject performed three consecutive repetitions of each of the maneuvers. Although a deflection in the vessel was observed during both maneuvers, only minimal variation in vessel diameter resulted. In the popliteal vein, weight bearing caused a mean change in diameter of 2.3% (mean difference for each participant: 1.6%, 0.1%, −1.2%, 1.5%, −0.9%) whereas toe curls caused a mean change in diameter of 1.2% (0.6%, −0.5%, −1.7%, −0.9%, −2.2%) compared with resting. For the posterior tibial vein, weight bearing caused a mean change in diameter of 4.8% (−5.3%, 1.7%, −6.1%, −6.2%, 4.9%) whereas toe curls caused a mean change in diameter of 1.6% (−2.6%, 3.8%, 1.8%, 2.6%, 2.3%).

It is reasonable to believe that similar diameter changes would have occurred while the ejected volume was recorded in the main study. As a consequence, the calculated margin of error for ejected volume estimation would be ~4.7% for the popliteal vein and ~9.84% for the posterior tibial vein during weight bearing and ~2.5% for the popliteal vein and ~3.3% for the posterior tibial vein during toe curls. These results suggest that weight bearing and toe curls had only a minimal effect on the diameter of these two vessels, and subsequently in the accuracy of the calculated ejected volume, based on their initial diameter.

The large volume of blood observed due to weight bearing is in line with the findings of Gardner and Fox (11), who stated that venous blood ejected from the PVP due to weight bearing could be observed proximal to the femoral vein. We have now shown that this increase in volume is also observed distal to the femoral vein, i.e., at the popliteal vein, and more distally, at the posterior tibial and peroneal veins. The applied force of weight bearing to the foot and the subsequent extension of the foot arch could cause the collapse of deep plantar veins and the longitudinal stretching of the deep plantar venous arch. This action could be responsible for the large observed outflow into the posterior tibial, peroneal, and, eventually, popliteal veins. However, this large outflow from the foot was not observed when IPC was used to empty the PVP. This may be because it was not possible to entirely avoid cocontractions of the calf muscles to assist balance during weight bearing, which may have enhanced the weight bearing results due to calf muscle pump activity. IPC may not provide the necessary force required to fully extend the foot arch and expel the same blood volume compared with resting. For weight bearing and toe curls, there was not possible to entirely avoid cocontractions of the calf muscles to assist balance during weight bearing, which may have enhanced the weight bearing results due to calf muscle pump activity. IPC may not provide the necessary force required to fully extend the foot arch and expel the same blood volume compared with resting. For weight bearing and toe curls, there was not possible to entirely avoid cocontractions of the calf muscles to assist balance during weight bearing, which may have enhanced the weight bearing results due to calf muscle pump activity. IPC may not provide the necessary force required to fully extend the foot arch and expel the same blood volume compared with resting.

The main veins that comprise the PVP are intermuscular in their course (3, 6). Weight bearing on the foot is quite a passive exercise, whereas toe curls are entirely muscular. It is likely that the plantar veins and the intramuscular branches may be compressed by the foot muscles against bone during the toe curl contraction, and therefore blood flow is elicited via a mechanical pumping structure (3). The large increase in volume observed due to toe curls suggests that there is also a muscle pump element involved in the venous emptying of the foot. However, foot NMES, as applied in this situation, was unable to produce a significant increase in venous blood volume compared with resting. As with weight bearing, the possibility of cocontractions of muscles during toe curls could not be avoided; it is not possible to perform a toe curl without contracting the flexor digitorum longus muscle. This may have compressed segments of the veins distal to the measurement point and further increased venous volume during toe curls. With NMES, this combination of muscle contraction was not possible. To rule out this possibility, one should take the

Fig. 7. Median bar charts (n = 6) of ejected venous volume through the anterior tibial veins in response to weight bearing, toe curls, IPC, and NMES. Error bars indicate the 75th percentile. The maneuvers had no significant effect on the volume of blood ejected into the anterior tibial veins (P = 0.077). There were no significant differences between the volumes in the superficial and deep anterior tibial veins (P = 0.539).
ultrasound measurement from the level of the medial malleolus in order to record venous volume directly as it leaves the foot. Pilot work showed that ultrasound measurement taken at the medial malleolus would not allow for consistent results across all subjects, and therefore we avoided it in the present study. However, a venous volume measurement of a single strand of the posterior tibial vein at the medial malleolus was possible in three additional subjects. No differences were observed when these measurements were compared with those from the same vein at the original site. This would suggest that there is no significant additional compression of the veins due to the flexor digitorum longus in the region of the calf distal to the measurement site. We may therefore assume that measurements taken in this study at one-third of the medial shank are representative of the quantity of blood exiting the foot.

Kaplan et al. (13) applied stimulation to one foot of a group of healthy subjects and observed peak venous velocities of ~50 cm/s in the popliteal vein. Kaplan et al. concluded that mild stimulation of the feet was a promising method of countering venous stasis. We recorded peak velocities of ~18 cm/s (13.6–22.1 cm/s) due to NMES at the popliteal vein. Blood expelled by electrical stimulation of the foot muscles in our application did not cause adequate compression of the foot pump to produce the blood flow results observed by Kaplan et al., despite achieving a noticeable flexion of the toes during each contraction. This could be due to the majority of participants’ inability to tolerate high stimulation intensities. Lower stimulation intensities will not recruit as many muscle fibers as can be achieved at higher intensities, and this will result in less muscle contraction force and consequently in a reduced pumping effect. It is possible that a longer stimulus duration could yield a larger ejected venous volume; however, we found that participants were unable to tolerate longer stimulus durations without causing the foot muscles to cramp.

Ejected venous volume measurements were significantly larger in the popliteal vein than in the distal veins. This is no surprise as the posterior tibial vein merges with the peroneal vein, which, in turn, merges with the anterior tibial vein to become the popliteal vein. Furthermore, it would be impossible to consider all sources of venous flow recorded at the popliteal vein (intramuscular veins and sinuses of the gastrocnemius-soleus, perforations from superficial veins). Ejected venous volume appeared to be distributed evenly among the posterior tibial and peroneal veins regardless of maneuver. The anterior tibial vein appeared to carry the smallest volume of blood. This is understandable because these veins originate from the dorsal arch of the foot and therefore are not directly influenced by the conditions under test. However, some blood does indeed flow through these vessels after compression of the foot muscle pump. This is probably due to the perforation of the deep plantar venous arch to the dorsum allowing some blood from the PVP to escape dorsally through the deep and superficial system (6).

Differences in expelled blood volume were also observed with the change in posture, with ~78% difference in volume. There was no significant change in the average blood flow velocity between the two positions ($P = 0.843$), but there was a significant increase in vessel diameter in the standing position compared with the supine position. This suggests that the hydrostatic gradient affected venous volume by affecting vessel diameter, which resulted in the lower volume of blood ejected from the PVP in the supine position. It is also possible that the hydrostatic pressures resulted in more filling in the upright posture than the supine posture, which may have contributed to the higher ejected volume observed (20).

It is reasonable to think that both the weight bearing compression of the plantar veins and the muscular contractions around these veins would be active at different points in the stance phase of the gait cycle. From the results of this study, it appears that, indeed, the two voluntary maneuvers, i.e., weight bearing and toe curls, play equally important roles in expelling blood from the foot. This is a promising start for a better definition of how much one can improve circulation with toe curl exercises and for the definition of possible repeated exercises and their impact. This exercise may be a big advantage for DVT prevention during long periods of immobility by reducing venous stasis. Moreover, it may be useful for combating venous insufficiency in standing professions, supplementary to calf muscle exercises such as heel rises. Toe curls can easily be performed in any setting, e.g., while bed bound and during long-haul flights. IPC is a widely used method of DVT prevention (9) most often considered in situations in which a patient is immobilized for extended periods of time such as after knee replacement (21) and hip replacement (10, 16) surgery. It is typically used until the patient is ambulatory. Foot NMES does not appear to be as effective as the more traditional calf NMES, which has reported peak venous velocities of 43 cm/s in healthy subjects (14). However, combined NMES of the calf and foot pump in patients with a compromised calf muscle pump, as seen with venous disease (1), may further increase popliteal vein peak velocities beyond the 13 cm/s due to calf stimulation reported by Clarke Moloney et al. (5). Further investigation of this venous return augmentation technique is required.

GRANTS

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DISCLOSURES

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