Anatomy of the veno-muscular pumps of the lower limb

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Abstract

Objective: To study the anatomy of the veno-muscular pumps of the lower limb, particularly the calf pump, the most powerful of the lower limb, and to confirm its crucial importance in venous return.

Methods: In all, 400 cadaveric limbs were injected with green Neoprene latex followed by an anatomical dissection.

Results: The foot pump is the starter of the venous return. The calf pump can be divided into two anatomical parts: the leg pump located in the veins of the soleus muscle and the popliteal pump ending in the popliteal vein with the unique above-knee collector of the medial gastrocnemial veins. At the leg level, the lateral veins of the soleus are the bigger ones. They drain vertically into the fibular veins. The medial veins of the soleus, smaller, join the posterior tibial veins horizontally. At the popliteal level, medial gastrocnemial veins are the largest veins, which end uniquely as a large collector into the popliteal vein above the knee joint. This explains the power of the gastrocnemial pump: during walking, the high speed of the blood ejection during each muscular systole acts like a nozzle creating a powerful jet into the popliteal vein. This also explains the aspiration (Venturi) effect on the deep veins below. Finally, the thigh pump of the semimembranosus muscles pushes the blood of the deep femoral vein together with the quadriceps veins into the common femoral vein.

Conclusion: The veno-muscular pumps of the lower limb create a chain of events by their successive activation during walking. They play the role of a peripheral heart, which combined with venous valves serve to avoid gravitational reflux during muscular diastole. A stiffness of the ankle or/and the dispersion of the collectors inside the gastrocnemius could impair this powerful pump and so worsen venous return, causing development of severe chronic venous insufficiency.

Keywords
Venous anatomy, veno-muscular pumps, calf pump, soleus veins, gastrocnemial veins, semimembranosus, CVD

Introduction

The muscular pumps are the true peripheral heart of the venous system of the lower limbs and play a crucial role in the venous return.

The basic function of the venous system of the lower limbs is to ensure the return of the blood from the peripheral tissues to the heart. In order to be efficient, the venous system is based on two mechanisms: the normal functioning of the venous valves (anti-reflux system against gravity) and a complex system of impulse-aspiration pumps, so-called veno-muscular pumps.

These pumps can be divided into four main parts, creating together a true chain of synchronized events, as it was stated 30 years ago by Gardner and Fox3:

- The foot pump, located in the lateral plantar veins.
- The leg pump, located in the soleus muscle.
- The gastrocnemial pump, acting at the popliteal level above the knee. These two latter pumps together are the calf pump, the most important pump of the limb.
- Finally, the thigh pumps: semi membranosus, biceps (posteriorly) and quadriceps muscle (anteriorly).

The synchronization of the different veno-muscular pumps during walk is crucial: foot, then leg, popliteal and finally thigh pumps.
The mechanisms against gravitational reflux and the major role of the venous valves

The venous valves play a key role allowing, during muscle contraction, the unidirectional venous flow to the heart, and avoiding reflux of blood due to the gravitational forces that occur during muscular diastole.4,5

A venous valve has two leaflets and its shape is similar to a pigeon's nest.4,6 Each valve has two faces, a "parietal" concave toward the heart and the other "axial" convex looking the lumen of the vein. Each valve thus defines with the wall a venous sinus whose bottom is distal and the proximal opening. The free edges of the two valves and their integration into the vein wall are called valvular horns. These are four in number.

The valves of the deep and superficial veins are located at particular levels, mainly next to the junctions of the tributaries, for hemodynamic reasons. These are called ostial valves. The others, located along the venous axis, are called truncal valves. The common locations of the valves along the femoro-popliteal axis are shown on Figure 1. These can be divided into three levels from the root of the limb distally: The Scarpa triangle (1 to 4), the femoral valves (5 to 8) and the popliteal valves (9 to 13).

The dynamic effect of the venous pumps is closely related to the anatomy of the venous valves:

Lurie and Kistner have introduced innovative concepts regarding the movements and orientation of venous valves leaflets and local hemodynamics. They first demonstrated that the blood forced by the muscular pumps through the orifice forms a jet with higher velocities in the center of the vein.4 This is explained by the fact that valve leaflets do not go all the way against venous wall and that, at the time of maximal opening, the orifice of the valve has a funnel shape. More recently, they observed that the relative position of venous valves is probably key to the efficacy of venous return.5 The angle of about 90° between two adjacent valves produces a helical flow, which optimizes the blood transport, altered as a result of the confluence of veins with different hemodynamic patterns.

Material and methods

We have studied 400 limbs of 200 non-embalmed cadaveric subjects (mean age of 84). All cadavers were derived from the Division of the "Don des Corps" in the department of Anatomy, University Paris Descartes, bequeathed by informed consent.

The technique of injection was described previously:9 after exposing the medial marginal vein, a no. 19 butterfly venous catheter was inserted and directed towards the toes (countercurrent to blood flow). A tube was inserted into the common femoral vein to perform lavage-irrigation with soupy water, repeated several times. Massage of the muscles was performed until a clear liquid was obtained. Then, after ligation of the femoral vein, green neoprene latex was injected (about 120 to 150 ml per limb), over 30 minutes. Dissection was started the next day. A colored segmentation was achieved by painting the veins in order to obtain a more comprehensive identification. In some cases, we added an iodine contrast agent to the latex injection and performed, prior to dissection, a multislice helical CT.10,11 This makes it possible to build a 3D reconstruction of the venous anatomy of the limb. A similar technique is used in our CVD patients to investigate the whole venous system.12-14
Results

We studied successively the foot pump, the leg pump (soleus), the popliteal pump (gastrocnemius) and the thigh pumps.

Reminder about the FOOT PUMP

The anatomy of the foot pump has been previously described. The Lejar's concept of the venous sole of the foot is incorrect: the true blood venous reservoir of the foot is deeply located in the plantar veins, between the plantar muscles. The medial and mostly lateral plantar veins converge into the plexus-shaped calcaneal crossroad, where the blood is ejected upwards into the two posterior tibial veins. In addition, several medial perforators of the foot directly connect the deep system (medial plantar veins) to the superficial venous system (medial marginal vein). This forms a true "medial functional unit," which is unique in the limb because the venous flow is directed from deep to superficial.

Physiologically, the plantar veins play an important role in the venous return since a venous reservoir of 25 ml of blood is mobilized upwards with each step during walking. The impairment of the foot pump by a static foot disorder should be considered an important risk factor for chronic venous disease and should be evaluated and corrected in patients with venous insufficiency. A relevant explanation is that any foot dysmorphism (mainly a flat or hollow foot) could reduce the efficacy of the foot pump, which has been shown to be responsible for impairment of the calf pump. In such cases, treatment with an inner sole will reduce both abnormalities and thereby improve the venous insufficiency and the symptoms of the patient, which are not always of venous origin.

The calf pump

The calf veno-muscular pump is the most important pump in the limb. It consists of the triceps suralis muscle (Figure 2) and can be distinguished into two parts: the leg pump, located in the veins of the soleus, and the popliteal pump located in the gastrocnemius muscle.

Anatomical description of the leg pump

a- Description of the soleus muscle.

The soleus muscle constitutes the deep part of the triceps suralis. It is a broad flat muscle situated immediately below the gastrocnemius. It arises from tendinous fibers at the back of the head of the fibula, and from the upper third of the posterior surface of the body of the bone; from the popliteal line, and the middle third of the medial border of the tibia; some fibers also arise from a tendinous arch located between the tibial and fibular origins of the muscle, in front of which the popliteal vessels and tibial nerve run. The fibers end in an aponeurosis which covers the posterior surface of the

Figure 2. The triceps suralis muscle. The calf pump is made by the triceps suralis muscle. (a) Superficial muscles (posterior view). (b) Lateral view of the leg. (c) Posterior view of the deep plan. The gastrocnemius muscle has two bodies, medial (bigger) and lateral. The soleus muscle is the deep part of the triceps suralis (in (c) the higher part of the gastrocnemius muscles are resected).
muscle, which, gradually becoming thicker and narrower, joins with the tendon of the gastrocnemius to form the tendo calcaneus (Figure 2).

Variations: Accessory head to its lower and inner part usually ending in the tendo calcaneus, the calcaneus or the tancinate ligament.

The gastrocnemius and soleus together form a muscular mass that is occasionally described as the Triceps surae; its tendon of insertion is the tendo calcaneus (tendo Achillis). It is the thickest and strongest tendon in the body.

The two anatomical slices of the leg (Figure 3) show the huge volume of the soleus at the mid-leg level. It is divided into two parts medial and lateral (bigger), separated by a thick septum. The soleus veins are clearly visible inside the muscle, each part being divided into central, close to the septum and peripheral, located laterally.

b- Anatomy of the veins of the soleus.

The overall systematization of the soleus veins is shown in Figure 4. To our knowledge, no such anatomical description has been described previously.

The medial veins of the soleus are smaller than the lateral veins of the soleus and are oriented horizontally in the peripheral part of the muscle (Figure 5) and vertically in the central part (Figure 4 and 6). These vertical and central veins join the midline at the proximal part of the muscle to connect the fibular veins more laterally.

The lateral veins of the soleus: The lateral view shows the large volume of the lateral veins of the soleus, directed vertically. They join in several trunks ending in the fibular veins, above the arcade of the Hallux flexor longus muscle (Figure 4). This explains why the fibular veins are much larger above this arcade. Below, they are contained into the fibrous, inextensible fibular canal. Above, they are dilated due to the arrival of those large lateral veins of the soleus.

In summary, the drainage of the veins of the soleus is divided into two parts: the medial veins horizontally into the posterior tibial veins and the lateral veins vertically into the fibular veins (Figures 4 and 7).

The superior vein or dorsal vein of the soleus (DVS) (Figures 8 and 9) has not been described previously. The specific landmark of this vein is the belly of the Plantaris muscle, located between the gastrocnemius and soleus muscles. It arises from the lower part of the lateral prolongation of the linea aspera and from the oblique popliteal ligament of the knee joint. It forms a small fusiform belly, from 7 to 10 cm long, ending in a long slender tendon (Figure 8) that crosses obliquely between the two muscles of the calf. It runs along the medial border of the tendo calcaneus to be inserted with it into the posterior part of the calcaneus.

Several variations of the DVS can occur.

The DVS is commonly reduced to a small pedicle following the belly of the plantaris muscle. It drains into the lateral gastrocnemial trunk 1 to 3 cm below

Figure 3. The soleus muscle shown on two anatomical slices of the mid-leg. (a) Slice below the apex of the calf. (b) Slice at the apex of the calf showing the lower part of the medial gastrocnemial muscle body. 1: Tibia; 2: Fibula; 3: Apex of the medial gastrocnemial muscle; 4: Tibialis anterior muscle; 5: Hallux extensor muscle; 6: Extensor digitorum muscle; 7: Tibialis posterior muscle; 8: Flexor digitorum; 9: Lateral part of the soleus; 10: Latero-septal area of the soleus; 11: Medio-septal area of the soleus; 12: Medial part of the soleus; 13: Tibial posterior pedicle (veins and artery) and tibial nerve; 14: Fibular pedicle inside the bony-fibrous canal of the Fibula (veins and artery); 15: Small saphenous vein; 16: Great saphenous veins and tributaries; 5: Central septum of the soleus muscle. (The lateral veins of the soleus are colored in green, the medial ones in blue.)
The anterolateral pedicle often receives perforators connected to the posterior tibial veins (Figure 14).

The anatomical dissection of Figure 12 shows the connections of the small saphenous trunk with both medial gastrocnemial veins and veins of the soleus. Many variations of the gastrocnemial veins can be observed: 2 to 12 pedicles inside the muscle (4.5 in average) have been described in the classification, including four distinct types, proposed by Aragao et al. Such classification is of no use in clinical practice.

**SSV and gastrocnemial veins** The termination of the SSV is highly variable. In varicose veins patients, the saphenous popliteal junction (SPJ) is present in about 70% of the cases. When present, the medial gastrocnemial collector frequently makes a common trunk (about 30%) with the SSV as shown in the 3D reconstruction of the Figure 13. The anatomy can be complex when there is no SPJ: the thigh extension of SSV has a high termination inside the muscles of the thigh (see paragraph 3.3). A rare case is the short termination of the SSV.
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Figure 7. Anatomical dissection of the veins of the soleus. This is a colored segmentation after latex injection and dissection of a right leg (lateral view). The big lateral veins of the soleus (1) are colored in green; they drain into the fibular veins (2, in pink). The smaller medial veins (3) are colored in blue. They drain into the posterior tibial veins (4, in light blue). Please notice the levels of the leg perforators, connected at the same level where the muscular veins join the deep venous axis. (8, 10 and 14 cm from the medial malleola on the left – 9, 12 and 18 cm from the knee joint on the right.) 5: Popliteal vein; 6: Dorsal or superior vein of the soleus muscle; 7: Tendo of the plantaris muscle.

Figure 8. Different types of the dorsal vein of the soleus (DVS). It could be a “weak” type (a) here, the DVS ends separately into the lateral root of the popliteal vein or a bigger vein draining the superior and dorsal part of the soleus muscle (b) making a common trunk with the lateral gastrocnemial veins and or the arch of the small saphenous vein. 1: popliteal vein; 2: Medial root of the popliteal vein; 3: Lateral root of the popliteal vein; 4: Arch of the small saphenous vein; 5: Medial gastrocnemial vein; 6: Lateral gastrocnemial veins; 7: Dorsal or superior vein of the soleus muscle; PM: Plantaris muscle; S: Soleus muscle.
Figure 9. Different types of “Dorsal veins of the soleus.”
Type A (on the left) shows a Y type of the DVS; here the soleus veins drain medially into the medial gastrocnemial veins and laterally into the lateral gastrocnemial veins. Type B (on the right) is a strong type of the VDS where the major part of the medial gastrocnemial veins joins the veins of the soleus.

Figure 10. Sagittal slice of the medial gastrocnemius muscle.
The origin of the gastrocnemial veins is a network (1) originating from the lower calf perforators (4, 5). They give birth to the two vertical pedicles inside the muscle: anterolateral (2) and posteromedial (3) joining into a unique collector (7) into the popliteal vein (P) below the saphenous popliteal junction of the small saphenous vein (8). Several perforators (6) connect the anterior pedicle to the posterior tibial vein (PT).

Figure 11. Modal anatomy of the gastrocnemial veins (drawing from an anatomical dissection showing the venous system inside the muscle). 1: Popliteal vein; 2: Medial gastrocnemial veins; 3: Antero-lateral pedicle; 4: Posteromedial pedicle; 5: Lateral gastrocnemial veins; 6: Dorsal vein of the soleus; 7: Small saphenous vein; 8: Sural nerve; 9: Central calf perforators; 10: Polar calf perforators; 11: Medial calf perforator; 12: Great saphenous vein; P: Popliteal muscle.

at the calf by an oblique connection to the great saphenous vein below the knee (Figure 14). The connection of the SSV with the gastrocnemial perforators remains the same.

Anatomy of the gastrocnemius nerves
The innervation of the gastrocnemius muscles is useful to know, due to the proximity of the arch of the SSV (Figure 15). The nerve of the medial gastrocnemius crosses the arch of the SSV superficially, close to the SPJ, and represents a real danger during endovenous procedures and surgery. Also, it frequently gives birth to the medial branch of the sural nerve.15

The nerve of the lateral gastrocnemius is not particularly close to the veins. It gives birth to the main superior nerves of the soleus.

The sural nerve (Figure 16) is the companion nerve of the inter-gemellar vein (also called “vein of
Figure 12. Anatomical dissection of the calf showing the gastrocnemius veins. 1: Popliteal vein; 2: Medial gastrocnemial veins; 3: Terminal collector of the medial gastrocnemial veins; 4: Small saphenous vein; 5, 6: Perforators of the soleus; 7, 8: Polar calf perforators which originate the gastrocnemius pedicles; 9: Lateral veins of the soleus (draining into the fibular veins); 10: Posterior tibial veins; 11: Fibular veins; 12: Dorsal vein of the soleus.

Figure 13. Common trunk of the medial gastrocnemial trunk with the SSV. (Posteromedial view of a 3D reconstruction from a veno-CT with injection.) 1: Popliteal vein; 2: Common trunk; 3: Medial gastrocnemial veins; 4: Small saphenous vein (sinuous and dystrophic, 7 mm in caliber); 5: Thigh extension of the SSV; 6: Normal great saphenous vein.

the sural nerve”). The tibial part of the nerve joins a lateral branch coming from the fibular nerve at the apex of the calf. Down this junction, the nerve is the companion of the SSV in the saphenous compartment, located very close to the vein. The companion artery is also a part of the sural pedicle, with the nerve and vein. This explains why echographic control in this area is mandatory in order to minimize the risk of arterial injection during sclerotherapy.

Relationship between anatomy and efficiency of the gastrocnemial pump

Anatomical patterns of some inefficient calf pumps due to the dispersion of the venous collectors of the muscles are shown on Figure 17. In fact, the power of the pump
is explained by the unique collector draining into the popliteal vein, producing a high-speed ejection of blood during the contraction of the gastrocnemius muscle.

**Anatomical description of the thigh pumps**

- Posteriorly, the biceps and particularly the semimembranosus muscles have important venous arcades in shape of a plexus. They are connected with the thigh extension of the SSV by number of perforating veins, deeply located inside the thigh.
- Anteriorly, the quadriceps femoris is the pump of the root of the thigh.

**The posterior pump of the thigh: the semimembranosus muscle**

- **Description of the semimembranosus muscle.**
  The semimembranosus muscle is located at the posterolateral aspect of the thigh. A slice of the lower thigh better shows the huge volume of this muscle (Figure 18). A number of veins are located inside the muscle, which constitutes the main pump of the
posterior thigh. A dilatation of those venous arcades inside the muscle has to be checked by USD. This would be the sign of a venous stasis.

b- Anatomy of the veins of the semimembranosus.
The veins inside the muscle are disposed in arcades well shown by the anatomical dissections. These arcades are large longitudinal plexus of veins inside the muscle. At the lower part of the muscle they are connected to the popliteal vein by two or three horizontal branches below the Hunter’s hiatus. Upwards, they drain into two branches of the deep femoral vein (Figures 19 and 20).

In summary the venous arcades of the semimembranosus have a number of anastomoses with the popliteal
axis and drain proximally into the deep femoral vein. This apparatus seems to play the role of a safety valve on the femoral vein axis, shunting the narrowed part created by the Hunter’s outlet. In fact, the flush of the gastrocnemial pump is so powerful that the popliteal vein cannot accommodate the whole flux of the blood if there is a stenosis or a simple narrowing of the Hunter’s canal (Figure 21). In such cases, a part of the outflow can be absorbed by the semimembranosus pump, and drained via the deep femoral vein.

**The anterior pump of the thigh: the quadriceps femoris**

**a- Description of the quadriceps femoris muscle.**

The quadriceps femoris includes four muscles on the front of the thigh. It is the great extensor muscle of the leg, forming a large fleshy mass that covers the front and sides of the femur. It is subdivided into four parts. One occupying the middle of the thigh, and connected above with the ilium, is named from its straight course the *rectus femoris*. The other three lie in immediate connection with the body of the femur, which they cover from the trochanters to the condyles. The portion on the lateral side of the femur is termed the *vastus lateralis*; that covering the medial side, the *vastus medialis*; that in front, the *vastus intermedius*.

**b- Anatomy of the veins of the quadriceps femoris.**

The muscular veins of this big mass drain mainly into a big trunk ending at the root of the thigh into the common femoral vein. This trunk often joins the deep femoral trunk to make a common trunk before its femoral termination (Figure 1).

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**Figure 19.** Anatomical dissection of the venous arcades of the semimembranosus muscle. The lower branches (3, blue dots) connect the arcades to the popliteal vein (1). The higher branches (4, green dots) are the way out into the deep femoral vein (2); 5: the fibers of the semimembranosus muscle; 6: Sciatic nerve; 7: Tibial nerve; 8: Fibular nerve.

**Figure 20.** Anatomical dissection of the calf and thigh pumps (posterior view of a right limb). 1: Popliteal vein (with valves in yellow); 2: Afferent branches; 3: venous arcades of the semimembranosus; 4: Efferent branches; 5: Deep femoral vein branches; 6: Arcades of the biceps muscle; 7: Thigh extension of the SSV (connected upwards to the venous arcades); 8: SSV 9: Medial gastrocnemial vein; 10: Lateral gastrocnemial vein; 11: Dorsal vein of the soleus; 12: Hunter’s hiatus; 13: Tibial nerve (resected).
Then, this action is taken over at the leg level by the leg pump of the soleus. The most important part of the leg pump is located in the lateral veins of the soleus, mainly draining vertically into the tibular veins in several pedicles, while the medial part is joining the posterior tibial veins by smaller horizontal collectors.

At the popliteal level above the knee joint, we observe the most powerful pump, the gastrocnemial pump. The unique collector of the medial gastrocnemial veins plays a major role here, providing a high-speed powerful ejection of blood into the popliteal vein, pushing the blood column upwards and producing an aspiration effect in the popliteal roots below.

Then, the thigh muscular pumps are activated. First the biceps and mostly the semimembranosus, with its venous arcades making a shunt between the popliteal vein and the deep femoral vein, and so playing the role of a safety valve.

Lastly the quadriceps muscle pump is connected at the root of the limb by the venous trunk of the quadriceps femoris, joining the external circumflex to connect into the common femoral vein.

The anatomical knowledge of the veno-muscular pumps, and particularly the calf pump, is crucial to better understand their major role in venous return. This knowledge helps explain the impact of ankle stiffness, which impairs the calf pump activation.

This anatomy is also useful to investigate the patients with venous disorders by DUS: for the venous mapping before a treatment, and to diagnose a calf DVT and follow its evolution.

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**Conflict of interest**

None declared.

**References**