Estimation of Nerve Dimensions from MRI of the Human Thigh

Joaquín Andrés HOFFER[1,3] Eli GIBSON[2,3] Burkhard MÄDLER[4,5] and Mirza Faisal BEG[2,3]

[1]School of Kinesiology, [2]School of Engineering Science, [3]Biomedical Engineering Program, Simon Fraser University, Burnaby, British Columbia, CANADA; [4]Phillips Medical Systems, Vancouver, British Columbia, CANADA; [5]High Field MR Centre, University of British Columbia, Vancouver, British Columbia, CANADA.

Abstract

We estimated the location of the sciatic nerve bifurcation and lengths and perimeters of tibial and peroneal nerve branches in 18 subjects, using optimized methods for obtaining high-resolution magnetic resonance (MR) images and generating 3D image reconstructions. This approach is suitable for non-invasive, pre-surgical assessment of peripheral nerve branching and critical dimensions in patients scheduled to receive neuroprosthetic implants.

1 Introduction

1.1 Rationale and Objectives

Emerging neuroprosthetic systems, such as the Neurostep™ assistive system for walking in hemiplegic patients [1], interface directly with peripheral nerves. The Neurostep™ includes two nerve cuffs installed around the tibial and peroneal nerves and a battery-powered pacemaker-like control unit implanted inside the thigh (**Fig. 1**).

Surgical implantation of nerve cuffs is normally a simple procedure. In some people, however, the sciatic nerve bifurcates into its tibial and peroneal nerve branches very distally, possibly too close to the knee for safe surgical implantation of cuffs. It is therefore of interest to determine in advance of a surgery, when possible, the levels of the thigh where the sciatic nerve bifurcates and where the tibial and peroneal nerve epineuria have definitely separated (**bifurcation level** and **separation level**; **Fig. 1**).

The objective of this study was to obtain normative data on sciatic nerve branching levels and nerve dimensions using magnetic resonance (MR) imaging in spinal cord injury, stroke, and control subjects.

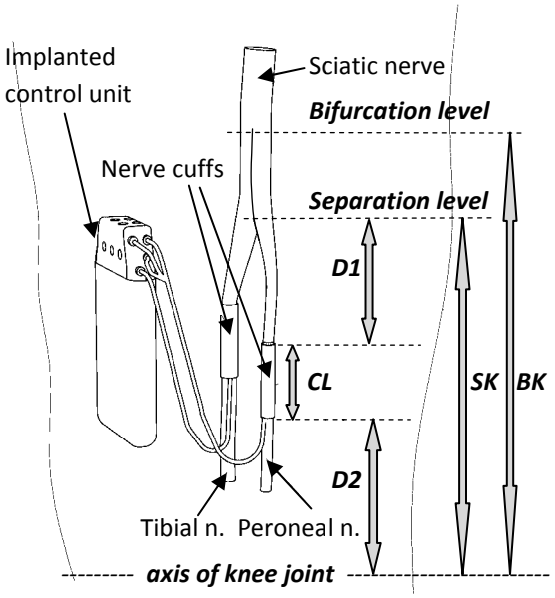


Fig. 1. Diagram of implanted Neurostep™ system. Two nerve cuffs, implanted on the tibial and peroneal nerve branches, are connected by flexible cables to a control unit in the medial thigh. ***D1*** = distance from nerve branch separation level to proximal cuff edge. ***CL*** = cuff length. ***D2*** = distance from distal cuff end to knee joint. ***SK*** = distance from nerve branch separation level to knee joint. ***BK*** = distance from sciatic nerve bifurcation to knee joint.

2 Methods

2.1 Image Acquisition and Analysis

To briefly describe our two-tier imaging protocol optimization approach [3], initial bilateral reference scans at coarse resolution provided a large field-of-view image of most of the thigh region, allowing for visual identification of anatomical landmarks and the level at which the sciatic nerve bifurcates. A subsequent measurement scan imaged a smaller portion of the thigh containing the region of the sciatic nerve bifurcation identified in the coarse scan. This scan was acquired at higher resolution, typically 0.5 – 1.0 mm axial and 2.5 – 5.0 mm out-of-plane, with no slice gap. The MR pulse sequence

parameters were chosen to achieve best tissue contrast and detail. The axial slices from the higher resolution scan contained sufficient detail to identify and delineate the nerves of interest (see example in **Fig. 2**) as well as anatomical structures such as the femur, femoral and popliteal arteries, saphenous vein, individual quadriceps and hamstring muscle heads, fat and skin layers. The perimeter and cross-sectional area of reconstructed sciatic nerve and its tibial and common peroneal branches could be measured in the axial slices.

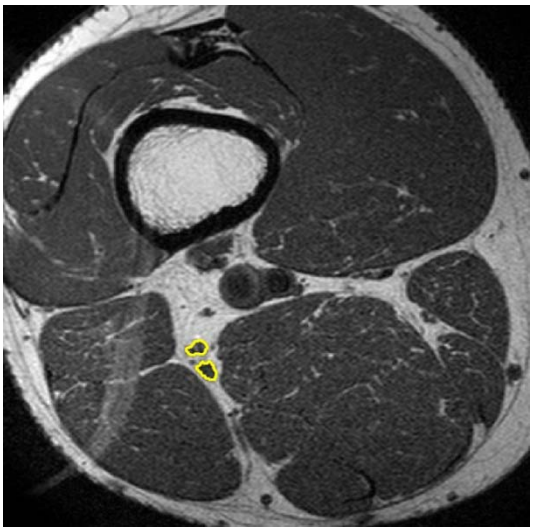
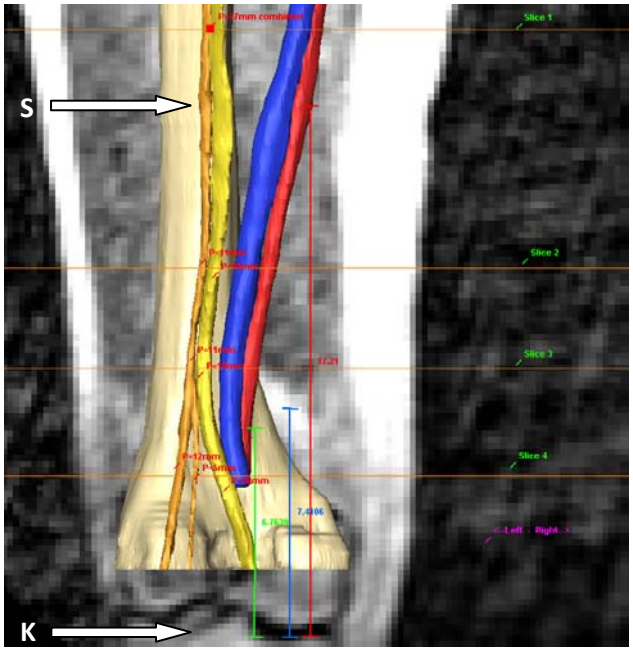


Fig. 2. High-resolution image of a transverse section through the right thigh, distal to the level of sciatic nerve bifurcation. Yellow traces indicate the perimeters of the common peroneal and tibial nerves (*Subject MFB*).

In most subjects, 100 sequential slices were acquired along the thigh, spaced at 2.5 mm intervals to cover a 25 cm region of interest with the sciatic bifurcation level located approximately midway. Data from these 100 axial slices were combined to create an accurate 3D reconstruction of internal thigh anatomy structures of interest. These images portray the 3D interactions of tissues in a way that is difficult to visualize using 2D slices alone. An example is shown in **Fig. 3**.

Fig. 3. 3D reconstruction of selected structures based on in-phase high resolution scan of the paretic left thigh in a hemiplegic subject (*SS*). Reconstructed tissues include bone (off-white), nerve (yellow), artery (red), vein (blue). ***Top arrow*** shows the level **S** where the common peroneal and tibial branches appeared separate from each other. ***Bottom arrow*** shows the bone landmark, **K** (distal end of internal condyle of femur). In this subject, **SK** = 17.2 cm.



3 Results

High-resolution, 3-D reconstruction images in one or both thighs were obtained from 18 subjects (3 spinal cord injured, 3 stroke and 12 controls, of both genders; age range 23-60). In total, 33 sciatic nerve branching patterns were analyzed (**Fig. 4**).

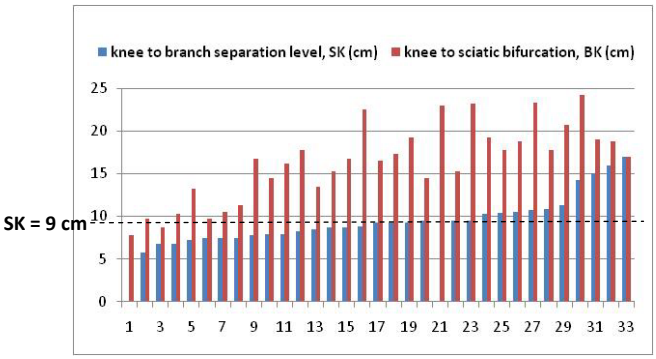


Fig. 4. Estimated locations of the sciatic nerve bifurcation level inside the thigh (**BK**, N=33) and the level where the tibial and peroneal nerve branches separated (**SK**, N=31).

As shown in **Fig. 4**, the distance from the knee joint to the estimated level of sciatic nerve bifurcation (**BK** in **Fig. 1**) ranged widely among subjects, between 7.75 cm and 24.25 cm (average= 16.4 cm, SD= 4.5 cm; N=33). The distance from knee joint to evident separation of tibial and peroneal nerve branches (**SK** in **Fig. 1**) also ranged widely, between 5.75 cm and 17.0 cm (average= 9.6 cm, SD= 2.7 cm; N=31).

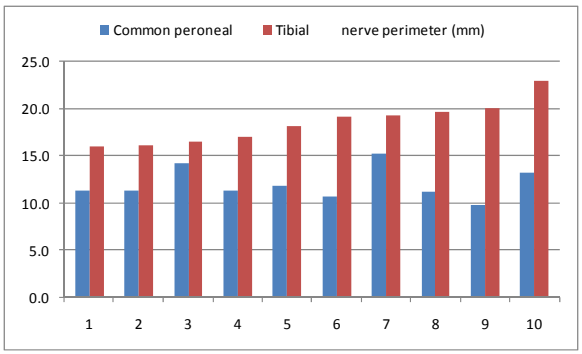


Fig. 5. Average cross-sectional perimeter of **tibial nerves** (**red**) and **peroneal nerves** (**blue**) measured 4 cm below the nerve separation level **SK** (N= 40 nerves, 10 subjects).

Nerve perimeters, measured 4 cm below the nerve separation level **SK**, varied considerably among subjects (**Fig. 5**). Average **tibial nerve perimeters** ranged between 16.0 and 22.9 mm (average = 18.5 mm, SD = 2.1 mm; N = 20 nerves in 10 subjects). Average **peroneal nerve perimeters** ranged between 11.4 and 15.3 mm (average = 12.1 mm, SD = 1.8 mm; N= 20 nerves in 10 subjects).

4. Discussion

In reference to **Fig. 1**, the Neurostep™ system for foot drop requires 30 mm nerve cuffs (**CL** = 3 cm) and distances **D1** ≥ 1 cm and **D2** ≥ 5 cm in order to install the cuffs sufficiently away from the region where the nerves must bend as the knee joint flexes. Thus, for safe cuff installation, the distance **SK** from knee joint to where the nerves naturally separate must be **at least 9 cm** (dotted line in **Fig. 4**). Our estimated values of **SK** indicate that this minimum length would be available in about half of the nerves (16 of 31) in these 18 subjects. In the other 15 of 31 nerves, **SK** ranged from 5.75 to 8.75 cm.

In subjects with **SK < 9 cm** the tibial and peroneal nerves, between sciatic bifurcation and separation levels, may remain in close proximity but in separate epineuria. For such subjects to receive 3 cm nerve cuffs, the tibial and peroneal nerves would need to be surgically separated. In all but 2 of 31 nerves in our sample, knee to sciatic bifurcation distance **BK** was > 9 cm; so technically the surgeon could dissect apart the nerves another 0.25 to 3.25 cm between separation and bifurcation levels. However, success with a mobilization procedure depends on the extent of vascularization and on the surgeon's judgment and ability to ensure patency of the microvascular anatomy. If **SK < 9 cm** and the tibial and peroneal nerves are embedded in a common vascular plexus, we recommend against carrying out a surgical nerve isolation procedure. High risk of hemorrhage and/or ischemia must be avoided, as damage would lead to subsequent scarring, and compression neuropathy.

In patients with SK < 9 cm, we recommend instead the simpler and safer option of placing a single multi-channel cuff around the sciatic nerve, above its bifurcation. In an animal model, an 8-channel sciatic nerve cuff allowed selective electrical recruitment of every major ankle muscle group [2]. For a clinical system like Neurostep™, we propose that one sciatic nerve cuff will provide sufficient selectivity to control the action of the target ankle muscle groups, as well as sense the relevant afferent activity patterns [1].

5. Conclusions

MR-based 3D imaging provides high-quality, precise information on level of peripheral nerve bifurcation, level of nerve branch separation and sizes of nerves in human thighs. This information can be invaluable to assess the options for neurosurgical procedures such as safe implantation of nerve cuffs in patients who require a neuroprosthetic implant.

6. References

[1] Hoffer J.A., Baru M., et al. Initial results with fully implanted Neurostep™ FES system for foot drop. IFESS 10th Ann. Conf., Montreal, p. 53-55, 2005.

[2] Desmoulin G., Hoffer J.A. Selective control of leg muscle activation patterns and ankle forces using a multi-chambered stimulation cuff implanted on the sciatic nerve. IFESS 11th Ann. Conf., Phila, 2007.

[3] Gibson E., Hoffer J.A., Mädler B. and Beg M.F. Optimal pulse-sequences for in-vivo 3T MR imaging of healthy human peripheral nerves (In revision).

7. Acknowledgements

Funded by a grant from Rick Hansen Man in Motion Research Fund to JAH and MFB. We thank Alex MacKay and the UBC High Field MR Centre for their helpful support, and Dr. P. Dhawan for facilitating access to hemiplegic patients.