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The effects of hip abduction on sciatic nerve biomechanics during terminal hip flexion

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ABSTRACT

Terminal hip flexion contributes to increased strain in peripheral nerves at the level of the hip joint. The effects of hip abduction and femoral version on sciatic nerve biomechanics are not well understood. A decrease in sciatic nerve strain will be observed during terminal hip flexion and hip abduction, independent of femoral version. Six un-embalmed human cadavers were utilized. Three Differential Variable Reluctance Transducers (DVRTs) sensors were placed on the sciatic nerve while the leg was flexed to 70° with a combination of $-10°$, 0°, 20° and 40° adduction/abduction. DVRT placement included: (i) under piriformis, (ii) immediately distal to the gemelli/obturator, (iii) four centimeters distal to sensor two. A de-rotational osteotomy to decrease femoral version 10° was performed, and sciatic nerve strain was measured by the same procedure. Data were analyzed with three-way analysis of variance and Bonferroni *post-hoc* analysis to identify differences in the mean values of sciatic nerve strain between native and decreased version state, hip abduction angle and DVRT sensor location. Significant main effects were observed for femoral version ($P = 0.04$) and DVRT sensor location ($P = 0.01$). Sciatic nerve strain decreased during terminal hip flexion and abduction in the decreased version state. An 84.23% decrease in sciatic nerve strain was observed during hip abduction from neutral to 40° in the presence of decreased version at terminal hip flexion. The results obtained from this study confirm the role of decreased femoral version and hip abduction at terminal hip flexion to decrease the strain in the sciatic nerve.

INTRODUCTION

The sciatic nerve is composed of roots originating in the ventral rami of L4-S3 that fuse to form a single trunk. The nerve exits from the pelvis through the greater sciatic notch anterior to the piriformis muscle (PM), then continues posterior to the obturator/gemelli complex and quadratus femoris muscle [1, 2]. Within the deep gluteal space, the sciatic nerve lies between the posteromedial aspect of the greater trochanter and ischial tuberosity, resting in close proximity to the posterior capsule of the hip joint and hamstrings muscles [2, 3]. Distal to the ischium the sciatic nerve separates into two terminal branches—the peroneal and tibial nerves [1, 4] although variations exist in 16–20% of the population [5].

Nerve elongation is proportional to increasing joint angulation. In a cadaveric study performed by Coppieters *et al.* [6] the sciatic nerve in a human cadaveric model showed a proximal excursion of ~28 mm during the straight leg raise test. Additionally, those authors reported strain of ~7% in the medial portion of the sciatic nerve during hip flexion to 70–80° with the ankle in dorsiflexion. Phillips *et al.* [7] found sciatic nerve strain in rats at hip joint level to be ~8–12%, while strain at proximal and distal levels was 5%.

Normal hip joint movement directly influences neural tissue stretching, compression and position [8]. Shacklock *et al.* [8] demonstrated hip flexion elongates the sciatic nerve bedding due to the posterior projection of the femoral head. A failure of neurodynamic mechanisms or abnormal biomechanics can result in pain and disability of musculoskeletal structure [2]. In the case of proximal femoral retroversion, the increased posterior orientation of the femoral head while the hip is in flexion may result in greater sciatic nerve excursion when associated to hamstring contracture. Therefore femoral retroversion may be a predisposing factor to abnormal sciatic nerve strain by potentiating the effects of excessive strain and compressive pathologies. The aim of assessing this factor is to evaluate the effect of femoral version on the strain of the sciatic nerve in terminal hip flexion with adduction (ADD) and abduction (ABD). It is hypothesized that sciatic nerve strain will be decreased in the presence of terminal hip flexion and hip abduction, independent of femoral version.

MATERIALS AND METHODS

Cadavers

A total of 12 hips from 6 fresh-frozen full cadaveric specimens were dissected to access the sciatic nerve. One cadaver was utilized for a pilot experiment. The remaining five cadavers underwent testing with the results reported in this manuscript. Four cadavers were male and one female. The average age at time of death was 64.2 years (range, 48–84). In total 12 sciatic nerve samples, from 10 hips, were utilized as a result of one cadaver presenting a bilateral bifid sciatic nerve within the deep gluteal space. The specimens were thawed to room temperature before experiments.

CT description

CT scans were performed on all five cadavers prior to testing with a General Electric Medical Systems LightSpeed RT16 XTRA (GE Healthcare, Buckinghamshire, UK). Imaging consisted of axial cuts from T12 to toes. The feet were stabilized in a neutral position and the knees at 0° flexion. Images were analysed in GE MediaViewer to determine the original femoral version and McKibbins index of the samples. Additional measurements include Lesser Trochanter Version, Femoral Neck Shaft Angle, and Acetabular Version [9–11].

Surgical procedure

Physical examinations of the hip, pelvis and spine were performed to ensure no pathologic state existed. Exclusion criteria comprised of a gross inspection for deformities that restricted motion and neural damage across the trajectory of sciatic nerve, or surgical intervention.

The cadaver was positioned laterally and the trunk was stabilized between two, 2 × 1 ft, boards fixated superior to the iliac crest. The examined leg was placed on the testing frame with the hip joint in a neutral position with the tibiotalar, and subtalar joints locked in neutral. The knee was fixated with two Steinmann pins at 0° extension. In this position the sciatic nerve is under tension and provides a suitable platform to place the DVRT sensors. Although the sciatic nerve is not slack, this position was seen to provide the most consistent data and reduce error by not having to normalize baseline nerve strain, as it varies between cadaveric specimens. The contralateral leg was rested on the dissection table with the hip and knee in 90° flexion, and taped to the table.

A posterolateral approach to the hip was made over the posterior one-third of the greater trochanter. The fascia lata was incised in line with the skin incision. The Gluteus Maximus was split and retracted medially in order to provide access to the deep gluteal space. A lateral line was drawn distal to the lesser trochanter with a surgical pen as a reference for the de-rotational osteotomy. A Hoffman II MRI (Stryker, Kalamazoo, MI, USA) external fixator system was then placed onto the posterolateral femur using four Schanz screws, two 8-mm connecting rods and eight pin-to-rod couplings. The femur was transversely cut 2 cm distal to the inferior base of the lesser trochanter. An anterolateral 3.5 mm compression plate (Synthes, Inc., West Chester, PA, USA) was placed over the cut and fixed with two dynamic screws (Synthes, Inc., West Chester, PA, USA) for rigidity (Figure 1A).

Strain measurement

Three Differential Variable Reluctance Transducers (DVRTs) (Microstrain, Burlington, VT, USA) with a stroke length of 6 mm and resolution of 1.5 μm measured sciatic nerve strain. DVRT placement included: (i) immediately distal to the piriformis, (ii) immediately distal to the Gemelli/Obturator Internus (GEM/OI) complex, (iii) four centimeters distal to sensor two (Figure 2A). These locations were chosen to represent the highest region of strain in the sciatic nerve, as seen in pilot experiments performed. The strain gauges were fixed onto the sciatic nerve using two custom-manufactured barbed pins (Figure 2B). No other manipulations to the sciatic nerve were made, and the nerve remained in continuity from the spinal roots to the foot. Calibration values provided by the manufacturer were used to convert voltage measurements (V) into length measurements (mm). DVRT was tarred prior to testing. Changes in strain were calculated based on the

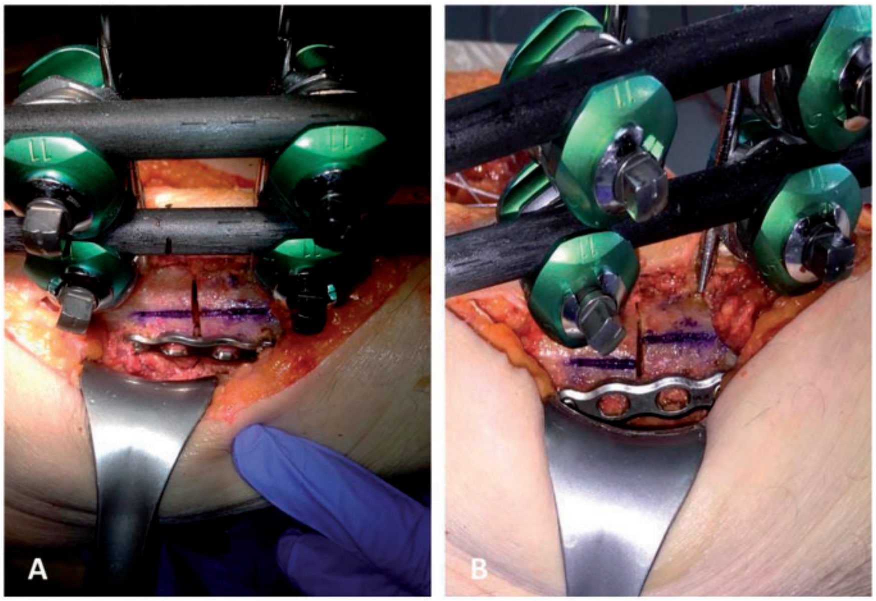

Fig. 1. (**A**) Surgical procedure to decrease femoral version 10°. Dark horizontal line was used as a reference for native version. A compression plate was added following the transverse cut for rigidity. (**B**) Femoral version decreased by 10° and locked in place with compression plate.

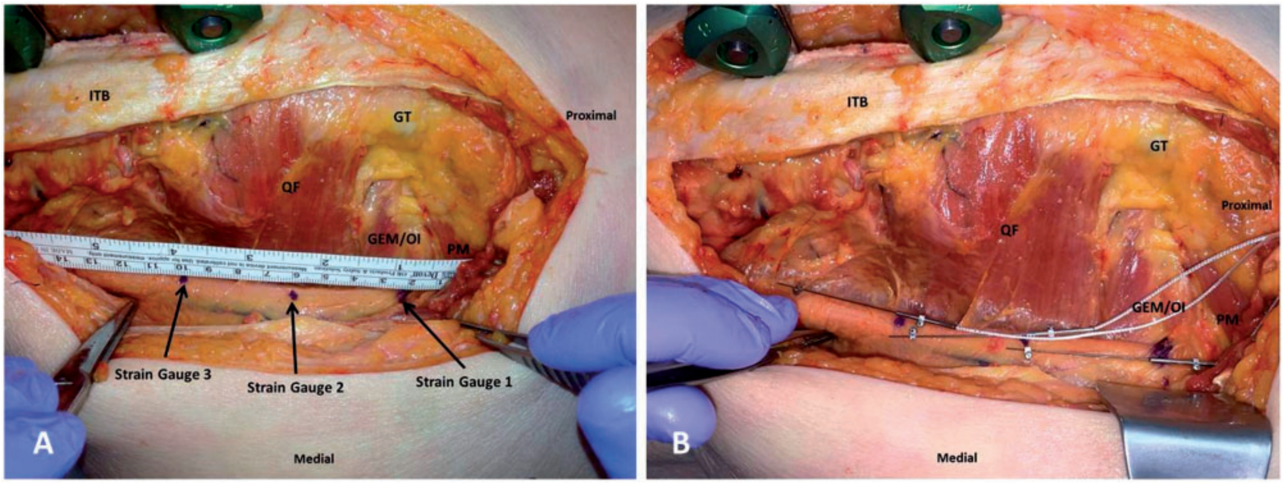

Fig. 2. Posterolateral approach to the left hip. Cadaver in lateral position. (**A**) Strain gauge placement: (i) Distal to PM, (ii) Distal to GEM/OI complex, (iii) Four cm distal to sensor two. (**B**) Placement of all three strain gauges. QF, quadratus femoris; ITB, iliotibial band; GT, posterior aspect of greater trochanter.

change in nerve length compared with the length in the arbitrary reference position. The investigators were blinded to the output of the strain gauges.

Measurements and hip positions

A PVC frame was built to provide support to the cadaver leg during the experiment. The 0° and 70° points were marked on the frame based on the center axis of the hip joint. No attachments were used during position manipulation to permit freedom of motion in the hip joint.

The leg was moved from 0° to 70° flexion in 10° adduction, 0°, 20° and 40° abduction (Figure 3). Adduction/abduction was measured with a goniometer by the same examiner for all experiments. The leg was held at 0° and 70° flexion for 10 s, and the timing was noted for data analysis; flexion was repeated twice. Flexion velocity from 0° to 70° was a slow and steady path; however this variable

Fig. 3. Frame with cadaver in 40° Abduction.

was not standardized in the trials. In the case of radical changes in signal progression, signifying strain gauge separation or entrapment, experiments were repeated.

Maximum values were determined using the documented time values for each position in conjunction with simulated charts of the data.

De-rotational osteotomy

A de-rotational osteotomy was performed to replicate decreased femoral version. The external fixator and compression plate were loosened and the femur (distal to the osteotomy) was externally rotated 10°. The resultant product of the osteotomy is a 10° decrease in femoral version when the foot is in 0° rotation. Successive experiments were executed using the protocol for testing hip positions to evaluate the effect of flexion and adduction/abduction on the strain of the sciatic nerve with the variable of decreasing femoral version (Figure 1B).

Statistical analysis

A three factor analysis of variance (ANOVA) was used to identify the mean differences in sciatic nerve strain between femoral version state, hip adduction/abduction angles and location of sensor. Femoral version factor was treated as a random effect, while hip adduction/abduction and location of sensor were treated as fixed effects. The statistical model for the three-factor experiment is:

$$\mathrm{Y}_{\mathrm{ijkl}} = \mu_{\ldots} + \alpha_j + \beta_k + \gamma_l + \alpha\beta_{jk} + \alpha\gamma_{jl} + \beta\gamma_{kl} + \alpha\beta\gamma_{jkl} + \epsilon_{ijkl}$$

where, Y_{ijkl}, sciatic nerve strain of each specimen; $\mu_{.}$ = represent mean effect of sciatic nerve strain; α_j, represents femoral version, $i = 1$ indicates native, $i = 2$ indicates retroversion, a ‘random’ effect; β_k, represents hip adduction/abduction, $j = 1$ indicates 10° adduction, $j = 2$ indicates 0° abduction, $j = 3$ indicates 20° abduction, j, 4 indicates 40° adduction a ‘fixed’ effect; γ_l, represents sensor location, $k = 1$ proximal, $k = 2$ indicates medial, $k = 3$ indicates distal, a ‘fixed’ factor; and ε_{ijkl}, represents error term for each subject.

Test of normality on residuals for sciatic nerve strain variable was assessed by Kolmogorov-Smirnov test, Box-Whisker plot, histogram and Q-Q plot. Variance homogeneity of the residuals on sciatic nerve strain variable was assessed by ‘White’ test and also by plotting the residuals against the predicted values. Homogeneity of variance assumption for three factors was tested by Brown and Forsythe’s test. Significant two- or three-way interaction

Table I. Cadaver specifications

Sample	*Age (years)*	*Sex*	*LTV (degrees)*	*FNSA (degrees)*	*ACEVER (degrees)*	*McKibbins (index)*	*FNV (degrees)*
1R	69	M	−42.6	135.8	16.2	12	−4.2
1L	69	M	−33	128.7	15.5	27.8	12.3
2R	84	M	−18.5	130.4	14	29.2	15.2
2L	84	M	−29.5	135.4	15.2	24.8	9.6
3R	60	M	−9.2	136.3	24.1	36.1	12
3L	60	M	−19.4	133.8	28	39.2	11.2
4R	60	M	−20.1	140.8	21.8	33.1	11.3
4L	60	M	−25	136.6	14.5	18.2	3.7
5R	48	F	−26.2	147.5	23	34.8	11.8
5L	48	F	−22.8	145.9	22.4	32	9.6
AVG	64.2		−24.63	137.12	19.47	28.72	9.25

R, right side; L, left side; M, male; F, female; LTV, lesser trochanter version; FNSA, femoral neck shaft angle; ACEVER, acetabular version; FNV, femoral neck version.

effects between femoral version, hip adduction/abduction and location of sensor were also analysed. No significant interaction effects ($P > 0.05$) were observed and these interaction terms were removed from the model and only main effects were analysed. All statistical analysis was performed using SAS 9.4 version (SAS Institute., Cary, NC, USA).

RESULTS

CT data

Descriptive anatomical data for the samples are available in Table I. CT images were analysed to calculate osseous measures. Average results for these measures include: Lesser Trochanter Version (−24.63°), Femoral Neck Shaft Angle (137.12°), Acetabular Version measured at the 3 o'clock position (19.47°) and the McKibbins Index (28.72). The average Femoral Version was 9.25° (range: −4.2° to 15.2°). A physical exam of each sample exhibited no occult pathologies or previous surgeries existed at time of testing.

Percent strain

Percent strain was calculated as the change in length of the three individual sensors over the initial length of the sensor, measured to be 61 mm. These measurements take into account the region of highest strain in the sciatic nerve. The strain in adduction/abduction and 70° of hip flexion between the native and decreased femoral version state, represented as percent strain, is seen in Figure 4.

The mean strain, denoted as '% strain', for the three sensor placements is represented in Table II. As the angle of abduction increased to 40° at terminal hip flexion, strain on the sciatic nerve decreased, with the exception of moving the leg from adduction to neutral. The de-rotational osteotomy to decrease femoral version by 10° further reduced the overall strain in the sciatic nerve.

ANOVA results

The three-factor ANOVA determined significant main effects for femoral version and DVRT sensor location (Table III). The mean change in sciatic nerve strain was significantly different between the native version and decreased version condition ($P = 0.04$). Significant differences occurred between the proximal and distal DVRT sensor placements compared with the medial DVRT sensor location ($P = 0.01$). No significant differences were observed for hip abduction angle. Strain measurement results are given in Table IV.

DISCUSSION

The results acquired from this cadaveric study propose a decrease in sciatic nerve strain in the presence of simulated decreased femoral version and increasing abduction. Following a de-rotational osteotomy to decrease femoral version 10° the strain in the length of the sciatic nerve

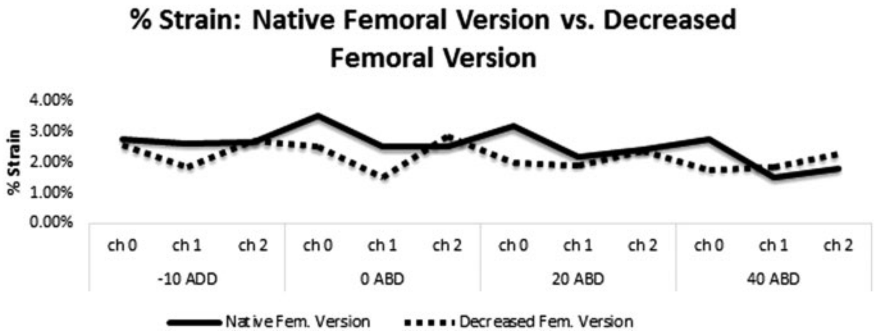

Fig. 4. Strain during 70° flexion. Ch. 0, 1, 2 refer to placement of Strain Gauge 1, 2, 3, respectively, on sciatic nerve.

Table II. Mean strain, represented as % strain, of all three strain gauge sensors at each abduction angle in 70° flexion

	−10ADD	*0ABD*	*20ABD*	*40ABD*
Native version	2.69%	2.85%	2.59%	2.02%
Decreased version	2.36%	2.28%	2.09%	1.96%
% change	−12.50%	−20.05%	−19.34%	−3.16%

The percent change after reducing the femoral version 10° is also shown

revealed a significant main effect ($P = 0.04$), compared with native femoral version. Decreasing nerve strain was observed as a result of increased abduction angle. Analysis of strain gauge measurements revealed the highest strain occurs in the proximal region of the nerve. A visual observation of the nerve kinematics revealed a ‘spiraling’ effect when moving the leg to terminal flexion. These factors are important for advanced knowledge of sciatic nerve protection, prehab/rehabilitation, stretch injury prevention, proximal hamstring injuries and understanding sciatic nerve kinematics.

Current literature examining sciatic nerve kinematics primarily focus on strain during hip flexion within a neutral range of adduction/abduction; in addition to the relationship between knee and ankle flexion/extension [6, 7, 12]. Animal sciatic nerve studies have resulted in a correlation between physiological changes and amplitude of activation potential with time, frequency, magnitude of pressure, stretch and strain among the factors [7, 12–16]. In 1979 Orf *et al.* [13], described repeated strain of 8–10% will result in a reduced slope of the stress-strain curve, in a rabbit model. These findings indicated that nerves endure less stress with successive elongations because of increased compliance and decreased stiffness. Acute strain higher than 10% or intermittent strain for more than 30 min will result in traumatic changes in blood flow and peak neural activation [12, 14]. Additionally Wall *et al.* [16] demonstrated that 12% strain can block nerve conduction after 1 h of stretch, with marginal activation during recovery, in a rabbit model. Therefore it is critical to understand how osseous anatomical structures, including decreased femoral version and adduction/abduction influence the sciatic nerve and surrounding tissues. Whereas innovative technological advancements for injury prevention are common, it is just as important to understand anatomical discrepancies. There are several factors including cadaveric specimens, nerve mechanics, anatomy and equipment that contributed to the findings.

Posterior hip pain as a result of sciatic nerve injury cannot be narrowed to only one type of injury. Anatomical factors such as decreased femoral version contribute to the wide array of sciatic nerve complications [4]. During hyperflexion maneuvers the sciatic nerve was seen to have a variable trajectory so as to avoid injury. The abduction angle decreased the amount of strain in the nerve and the decrease in femoral version further reduced the strain. The observation of a 3.54% decrease in strain as a result of decreasing the femoral version was observed between 0° and 20° hip abduction. Increasing the hip abduction from 20° to 40°, the strain in the sciatic nerve decreased 83.65%. The largest decrease in strain following the derotational osteotomy to decrease femoral version was 84.23% occurring between neutral and 40° abduction. The authors hypothesize that abduction increases the space between the ischial tuberosity and the lesser trochanter, also known as the ischiofemoral space (IFS). During full extension/0° flexion with 0° hip abduction the sciatic nerve is relaxed. When the hip was flexed at increased angles of abduction, the sciatic nerve remained outside of the ischial tunnel and less strain was observed through all sensor recordings. Gross sciatic nerve pathways were directed laterally outside of the ischial tunnel as the IFS increased with hip flexion.

Table III. The three-factor ANOVA results

Source	*DF*	*Type III SS*	*Mean square*	F *value*	*Pr > F*
Femoral version	1	3.63418441	3.63418441	3.91	0.04*
Hip abduction	3	5.48783369	1.82927790	1.97	0.11
DVRT sensor location	2	7.78113105	3.89056553	4.19	0.01*

Significant main effects were observed for femoral version and DVRT sensor location

Table IV. Sensor locations were immediately distal to the piriformis muscle (Piri), immediately distal to the GEM/OI complex and 4 cm distal to the Quad sensor (4 D)

		Hip abduction angle			
Femoral version state	*Sensor location*	***10ADD*** *(mm)*	***0ABD*** *(mm)*	***20ABD*** *(mm)*	***40ABD*** *(mm)*
Native ($n = 12$)	Piri	1.69 ± 1.04	2.15 ± 1.12	1.93 ± 0.92	1.69 ± 0.60
	GEM/OI	1.61 ± 1.50	1.53 ± 1.25	1.32 ± 1.03	0.92 ± 0.80*
	4D	1.62 ± 1.19	1.53 ± 1.00	1.49 ± 0.90	1.10 ± 0.81
Decreased ($n = 12$)	Piri	1.56 ± 0.98	1.53 ± 1.24	1.20 ± 0.91	1.07 ± 0.71
	GEM/OI	1.11 ± 0.79	0.90 ± 0.80	1.17 ± 1.05	1.13 ± 0.91
	4D	1.64 ± 0.89	1.74 ± 0.82	1.46 ± 0.67	1.38 ± 0.90

Add, adduction; Abd, abduction. *Significant difference in strain at 40Abd versus 0Abd, $P < 0.05$

The highest sciatic nerve strain was found in the most proximal DVRT sensor, noted throughout all test parameters. This sensor was placed immediately distal to the PM. A 27% decrease was observed between the sensors 1 and 2, and a 23% decrease between the numbers 1 and 3 DVRT sensors in all native test parameters. A significant main effect was observed for sensor location, with the medial sensor being significantly different than the proximal and distal sensor ($P = 0.01$). These findings can be supported by neurodynamic assessments reported by Phillips *et al.* [7], in which increased sciatic nerve strain occurred closer to the level of the hip joint. Subsequently there was a 19% decrease between the first and second sensor, and a 15% increase between the first and third sensor following the de-rotation. The absence of consistent data reflects no significant impacts on terminal flexion.

The trajectory of the nerve during terminal hip flexion is critical to understanding peripheral sciatic nerve mechanics. Careful observations during testing revealed that the sciatic nerve does not only elongate longitudinally, but more importantly has a torsional characteristic to the medial line when approaching terminal hip flexion. To the authors knowledge this concept of a ‘spiraling’ effect has yet to be described in literature. A possible explanation for this movement involves the alignment of the sciatic nerve epineurial, endoneurial and perineurial fibers. The Bands of Fontana have been described to have a recoiling effect, as seen in a ‘metallic coil spring’, when distraction is removed. Further investigation revealed that endoneurial fibers spiral around each other [17, 18]. Variations in collagen fiber arrangement between the layers help to protect the nerve fascicles from longitudinal tension and compression [19]. The direction of fibers that form obliquely, as determined in histological sections, are consistent with the current authors’ visual observations seen in the sciatic nerve kinematics. Subsequent studies should use optical tracking devices to measure the 3D pathway of the nerve in flexion and abduction.

Coppieters *et al.* described 28 mm of sciatic nerve excursion; these results were not replicated in this study due to the spiraling of the nerve. No mentions to medial or lateral movement were specified in the Coppieters article so it is assumed that excursion is solely longitudinal. This observation can be attributed to several factors in experimental design. One explanation is Coppieters *et al.* utilized embalmed cadavers, while this study utilized fresh-frozen cadavers. The absence of a tissue fixative in the fresh cadavers may explain the dissimilarity in excursion found in this study. Although fresh frozen may be ideal, considerable variables are associated with each sample. Additionally the surgical procedure differed in that Coppieters excised native connective tissue and muscles, while this study left all tissue intact, especially the fascial tissue connected to the nerve. Finally, three strain gauges were used in this study. These deviations may explain how the spiraling occurrence and similar excursion data were not described in previous literature.

A critical observation during testing revealed that the sciatic nerve would lose the intrinsic elasticity during consecutive flexion movements, resulting in a slack nerve that would become less responsive to the flexion. This phenomenon can be explained by Orf *et al.* [10] in a study using rabbits. Stress curves portrayed a decrease in overall resiliency following repeated excessive straightening of the nerve. Flexion to 70° was chosen because not all cadavers had the ability to reach higher levels of flexion due to age and hamstrings tightness.

Utilization of the information obtained from this study may have clinical applications for post-operative rehabilitation and identifying underlying sciatica pain. A potential use includes sciatic neural glides while the hip is in abduction or with limiting of terminal hip flexion to relieve sciatic nerve strain. Additional use may apply to hamstring avulsions that result in the scarring, traction, or detached nerve branches that occurs during the proximal hamstrings rupture [20, 21]. In this case the proximal hamstring tendons will scar the sciatic nerve tissue over time [22].

LIMITATIONS

The presence of a bifid sciatic nerve may have contributed negative effects to the overall results since the terminal branches have different individual biomechanical characteristics compared with an intact sciatic nerve. Additionally, the bifid sciatic nerve is not a common occurrence in the population. The tested native sciatic nerve state occurred with 0° knee extension and the tibiotalar and subtalar joints fixed in a neutral position. In this position, an intrinsic nerve strain is present, and therefore the observed nerve strain measurements may be underestimated in comparison to a true zero native state. The experimentation sequence used was not randomized and the authors recommend future experiments use a randomization procedure.

CONCLUSION

The results obtained from this study confirm the role of decreased femoral version and hip abduction at terminal hip flexion to decrease the strain in the sciatic nerve. The findings may be important in the advanced understanding of sciatic nerve biomechanics.

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CONFLICT OF INTEREST STATEMENT

None declared.

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