Published in final edited form as:

J Biomech. 2010 March 3; 43(4): 778–782. doi:10.1016/j.jbiomech.2009.10.031.

Transient Decreases in Forelimb Gait and Ground Reaction Forces Following Rotator Cuff Injury and Repair in a Rat Model

Joseph J. Sarver, PhD^{*}, Michael I. Dishowitz, BS^{*}, Soung-Yon Kim, MD^{**}, and Louis J. Soslowsky, PhD

^{*} McKay Orthopaedic Laboratory, University of Pennsylvania, Philadelphia PA

^{**} Orthopaedic Surgery, Kangwon National University Hospital, Kangwon-Do, South Korea

Abstract

Due to inadequate healing, surgical repairs of torn rotator cuff tendons often fail, limiting the recovery of upper extremity function. The rat is frequently used to study rotator cuff healing; however, there are few systems capable of quantifying forelimb function necessary to interpret the clinical significance of tissue level healing. We constructed a device to capture images, ground reaction forces and torques, as animals ambulated in a confined walkway, and used it to evaluate forelimb function in uninjured control and surgically injured/repared animals. Ambulatory data were recorded before (D-1), and 3, 7, 14, 28 and 56 days after surgery. Speed as well as step width and length were determined by analyzing ventral images, and ground reaction forces were normalized to body weight. Speed averaged 22 ± 6 cm/sec and was not affected by repair or time. Step width and length of uninjured animals compared well to values measured with our previous system. Forelimbs were used primarily for braking ($-1.6 \pm 1.5\%$ vs $+2.5 \pm 0.6\%$), bore less weight than hind limbs ($49 \pm 5\%$ vs $58 \pm 4\%$), and showed no differences between sides ($49 \pm 5\%$ vs $46 \pm 5\%$) for uninjured control animals. Step length and ground reaction forces of the repaired animals were significantly less than control initially (days 3, 7 and 14 post-surgery), but not by day 28. Our new device provided uninjured ambulatory data consistent with our previous system and available literature, and measured reductions in forelimb function consistent with the deficit expected by our surgical model.

Keywords

rotator cuff repair; rat model; upper extremity function; ground reaction forces; step length

INTRODUCTION

Tears in the rotator cuff tendons of the shoulder result in pain and lost function (Tempelhof, et al., 1999). Surgery is often required to repair the tear; however, these repairs frequently fail, ultimately limiting functional recovery (Bishop, et al., 2006; Galatz, et al., 2004). The rat has emerged as a commonly used model for studying rotator cuff tendon pathologies in general (Schneeberger, et al., 1998; Soslowsky, et al., 1996), and rotator cuff repair specifically (Cohen,

CORRESPONDING AUTHOR: Louis J. Soslowsky, PhD, 424 Stemmler Hall, 36th & Hamilton Walk, Philadelphia PA 19104, Fax: (215) 573-2133 Phone: (215) 898-8653, soslowsk@upenn.edu.

CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest with any of the equipment used in this study or funding sources.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

et al., 2006; Dines, et al., 2007; Galatz, et al., 2004; Ide, et al., 2009; Iwata, et al., 2008; Lin, et al., 2007; Murrell, 2007; Szomor, et al., 2006; Thomopoulos, et al., 2003; Zalavras, et al., 2006). It remains difficult, however, to interpret the clinical significance of such tissue level studies without a measure of forelimb function.

Skilled reaching is the most common method for assessing forelimb function in the rat (Alaverdashvili, et al., 2008), but does not measure forces exerted by the forelimb. Locomotive analysis on the other hand, commonly uses force-plates and has historically been used to study both lower and upper limbs following central nervous system injury (Childs, et al., 2004; Clarke, 1995; Giszter, et al., 2008; Kanagal and Muir, 2007; Kanagal and Muir, 2008; Knoll, et al., 2004; Muir and Whishaw, 1999; Muir and Whishaw, 1999; Muir and Whishaw, 2000). There are few examples of locomotive analysis following orthopaedic injuries in general (Best, et al., 1993; Davidson, et al., 1997; Fu, et al., 2009; Messner, et al., 1999; Murrell, et al., 1993). However, our lab was the first to evaluate forelimb function by analyzing paw-prints following rotator cuff injury (Perry, et al., 2009). To date, no study has measured ground reaction forces (kinetic) in rats following rotator cuff repair; therefore, the objectives of this study were to: 1) construct an instrumented walkway capable of measuring paw-prints and ground reaction forces and 2) use the walkway to evaluate forelimb function following rotator cuff injury and acute repair. We hypothesized that: 1) paw-print parameters of uninjured animals from our newly constructed system would be consistent with those of our previous system (Perry, et al., 2009), 2) differences between limb kinetic data would be consistent with the literature, and 3) paw-print and kinetic parameters would decrease initially, but return to control at later time points.

METHODS

Instrumented Walkway

The instrumented walkway was similar to other rat locomotor walkways (Clarke and Parker, 1986; Giszter, et al., 2007; Howard, et al., 2000; Muir and Whishaw, 1999). Specifically, a clear acrylic (15 mm thick) walkway was confined to a width of 100 mm by two clear acrylic walls (130 mm high). Two 6 degree-of-freedom miniature (17 mm diameter) force/torque cells (nano17, ATI Industrial Automation, Apex North Carolina) were mounted to two 70 mm long acrylic force plates (15 mm thick), which were placed 150 mm from the walkway entrance. A 2 mm gap prevented loads transferring between plates and the walkway. A darkened box was placed 600 mm from the entrance of the walkway to encourage the animals to walk. Mirrors were placed along the sides of the walkway, so that a digital camera (A601fc, Basler Vision Technologies, Ahrensburg Germany) placed beneath the walkway captured both ventral and sagittal (left and right) views of the animal simultaneously (see figure 1). Force plate data were sampled at 1000 Hz and average filtered ($n=10$), and images were captured at 60 frames-per-second using software written in Labview (v8.2, National Instruments, Austin Texas). Kinetic data were subsequently interpolated at the times of image capture using MATLAB (v7.3 The Mathworks Inc, Natick Massachusetts).

Experimental Design

Sixteen male Sprague-Dawley rats (470 ± 20 grams) were used in this study (University of Pennsylvania's Institutional Animal Care and Use Committee approved). Animals were randomly assigned to uninjured or repaired groups. Uninjured animals underwent no procedures to the shoulder and served as control; repaired animals underwent unilateral detachment and acute repair of the left supraspinatus tendon as described (Thomopoulos, et al., 2003).

Rats were acclimated to the instrumented walkway on 5 different occasions prior to first recording ambulatory data (day -1). For both the repaired and uninjured groups, ambulatory data were collected the day prior to surgery (day -1), and at 3, 7, 14, 28, 42 and 56 days post-surgery. At each time point, at least two walks were recorded per animal as well as the animal's body weight.

Paw Print Analysis

A mask was created for each paw by selecting the apex of each toe from calibrated ventral images. Step width and length were calculated as the difference between the left and right forepaw mask centroids in the medial/lateral (x figure 1) and fore/aft (y figure 1) directions respectively (see figure 2). Speed was determined as the distance between the left forepaw centroids of the first and second paw-strike divided by the time between strikes. All analyses were performed using MATLAB.

Kinetic Analysis

To analyze kinetic data, the paw in contact with the plate of interest was identified visually (from both ventral and sagittal views). Trials were excluded if the animal stopped on the walkway, or if a paw spanned both force plates. In order to compare our data with the literature, we analyzed kinetic data for all limbs. To address our third hypothesis (comparing repaired to uninjured groups), we analyzed kinetic data acting on the left forelimb only.

Peak vertical (+z direction), braking (-y direction), propulsion (+y direction), and lateral (+/-x direction depending on left or right limb) forces were determined for each walk (see figure 3). These parameters were averaged across walks on a given day for each animal and normalized to the animal's body weight for that day.

Data from a Previous Study

We compared uninjured stride data from this study to uninjured stride data from a previous study in our laboratory (Perry, et al., 2009). In that study, rat paw-prints were recorded on bromophenol blue treated paper (which turns blue when it comes in contact with the animal's wet paws) and the width and length between the left and right forepaws were measured.

Statistical Analyses

Step length and width from the instrumented walkway were compared to data from our previous system using a Levene's test for variance and a two-tailed t-test for means with significance set at $p < 0.05$. In addition, for the uninjured day-1 data, kinetic parameters for all limbs were compared using two-sided paired t-tests with significance set at $p < 0.05$.

Speed, step and kinetic parameters of the uninjured and repaired groups were compared using a 2wayANOVA to study the effect of time and group (uninjured vs. repaired) and post-hoc t-tests were made when appropriate (Bonferroni corrected) $p < 0.05/6$.

RESULTS

Comparisons to Previous Study

There was no significant difference in either variability or mean between the instrumented walkway and our previous system (Perry, et al., 2009) for measures of both step width and length (see table 1).

Uninjured Ambulatory Data

Prior to injury, animals ambulated at an average speed of 22.2 ± 5.6 cm/sec, indicating they walked (Clarke, 1995). Average fore/aft forces (F_y) were negative (braking) for the forelimb, but positive (propulsion) for the hindlimb. In addition, peak vertical and lateral forces were smaller for the forelimbs compared to the hindlimbs (significant for both left and right pairs). Finally, there were no significant differences between left and right sides of either the forelimbs or hindlimbs for any measured parameters.

Post-Repair Results

The effects of both time and group (uninjured vs. repaired) on speed (Table 3) or step width (Table 3) were not significant. The effects of both time and group on step length were significant. Specifically, step length (Table 3) was significantly smaller for the repaired compared to the uninjured group at early time points (days 3 and 7), but not different at later time points. In addition, step length decreased from day -1 at early time points (days 3 and 7) and increased at day 42 for the repaired group, and was not different from day -1 for the control group except for days 7 and 42.

Kinetic data were not available for the left forelimb at the day 3 time point, since most animals placed no weight on that limb. The effects of both treatment and time on peak vertical force (Table 3) were significant. Specifically, the repaired group was significantly less than uninjured at days 7 and 14, but not different at later time points. Furthermore, force decreased from day -1 at day 7, for the repaired group only.

The effects of both treatment and time on peak braking, but not propulsion, force ($-F_y$ and $+F_y$ Table 3) were significant. Specifically, braking force of the repaired group was significantly less than uninjured initially (day 7), but not different at later time points. There were no significant differences from day -1 at any time point for either the repaired or uninjured groups.

Finally, treatment had a significant effect on peak lateral force (F_x Table 3). Specifically, peak lateral force of the repaired group was greater at day -1 and lesser at day 7 than the uninjured group.

DISCUSSION

Consistent with our first hypothesis, there were no differences in either step length or width between our newly constructed walkway and our previous system (Perry, et al., 2009), suggesting that ambulation was unaffected by the measurement system. Furthermore, despite the relatively slow speed (22 ± 6 cm/sec) (Giszter, et al., 2008; Thota, et al., 2005; Webb, et al., 2003), comparisons between limbs (Table 2) were consistent with available literature on uninjured Sprague-Dawley rat ambulation (Giszter, et al., 2008; Webb, et al., 2003). Specifically, forelimbs supported less weight than hindlimbs (Webb, et al., 2003), were used primarily for braking (Giszter, et al., 2008) and were not different between sides (Webb, et al., 2003), providing confidence in our system and supporting our second hypothesis. Lastly, the low variability (5% standard deviation) in control data, suggests that difference as small as 7% could be detected with this system.

Consistent with our third hypothesis, both stride and kinetic parameters for repaired animals decreased initially, but returned to control by 4 weeks, indicating that there was no permanent loss in function following surgery. Interestingly, the forces which decreased (vertical and braking) indicate a reduced ability to produce a forward-flexion moment at the shoulder, the same moment produced by the supraspinatus and deltoid (Kanchiku, et al., 2008), and therefore consistent with injury caused by our surgical repair.

As with any study, there are several limitations. While we recorded at least 2 trials for each animal at a given time point, subsequent analyses occasionally left only 1 or no trial, making it difficult to perform a repeated measures analysis. Despite this, our uninjured results were consistent with the literature in which averages of 10 or more trials per animal are sometimes reported (Giszter, et al., 2008). In addition, we did not control for speed, which is known to affect measured parameters (Koopmans, et al., 2007). Importantly, we found that surgery did not have a significant effect on speed and therefore our results are not confounded by this factor. We did not measure shoulder position, thus, inferences about the moments at the shoulder are based on gross observations of the shoulder relative to the paw from viewing sagittal images, as well as the literature (Fischer and Blickhan, 2006). This may be the subject of future studies, and would allow us to further quantify shoulder function. Lastly, repair was compared to uninjured rather than a sham repair because the aim of this study was to validate the system, rather than assess the effectiveness of our repair.

In conclusion, this study demonstrated that measures of forelimb function in our rat model (step and kinetic ambulatory data) using our newly constructed device are similar to data from our previous system and the literature, and that following supraspinatus injury and acute repair, function decreased initially, but returned to control values within 4 weeks. Decreases in ground reaction force indicate a reduced ability of the shoulder to produce forward flexion moments, the primary moment generated by the injured tissues in the rat. This system can be used in future studies to determine if the permanent loss in function following larger cuff tears shown previously (Perry, et al., 2009) can be restored following surgical repair.

Acknowledgments

This study was supported by a grant from the NIH/NIAMS (AR051000) and the NIH/NIAMS supported Penn Center for Musculoskeletal Disorders (AR050950). The authors thank Willis Zhu and Eric Cohen for their help in analyzing ambulatory data and Stephanie M. Perry, Noel Camacho and Ehren Carine for their help in designing the instrumented walkway.

References

1. Tempelhof S, Rupp S, Seil R. Age-related prevalence of rotator cuff tears in asymptomatic shoulders. *J Shoulder Elbow Surg* 1999;8(4):296–299. [PubMed: 10471998]
2. Bishop J, Klepps S, Lo IK, Bird J, Gladstone JN, Flatow EL. Cuff integrity after arthroscopic versus open rotator cuff repair: a prospective study. *J Shoulder Elbow Surg* 2006;15(3):290–299. [PubMed: 16679227]
3. Galatz LM, Ball CM, Teefey SA, Middleton WD, Yamaguchi K. The outcome and repair integrity of completely arthroscopically repaired large and massive rotator cuff tears. *J Bone Joint Surg Am* 2004;86-A(2):219–224. [PubMed: 14960664]
4. Schneeberger AG, Nyffeler RW, Gerber C. Structural changes of the rotator cuff caused by experimental subacromial impingement in the rat. *J Shoulder Elbow Surg* 1998;7(4):375–380. [PubMed: 9752647]
5. Soslowsky LJ, Carpenter JE, DeBano CM, Banerji I, Moalli MR. Development and use of an animal model for investigations on rotator cuff disease. *J Shoulder Elbow Surg* 1996;5(5):383–392. [PubMed: 8933461]
6. Cohen DB, Kawamura S, Ehteshami JR, Rodeo SA. Indomethacin and celecoxib impair rotator cuff tendon-to-bone healing. *Am J Sports Med* 2006;34(3):362–369. [PubMed: 16210573]
7. Dines JS, Grande DA, Dines DM. Tissue engineering and rotator cuff tendon healing. *J Shoulder Elbow Surg* 2007;16(5 Suppl):S204–207. [PubMed: 17524676]
8. Ide J, Kikukawa K, Hirose J, Iyama K, Sakamoto H, Fujimoto T, Mizuta H. The effect of a local application of fibroblast growth factor-2 on tendon-to-bone remodeling in rats with acute injury and repair of the supraspinatus tendon. *J Shoulder Elbow Surg* 2009;18(3):391–398. [PubMed: 19393930]

9. Iwata Y, Morihara T, Tachiiri H, Kajikawa Y, Yoshida A, Arai Y, Tokunaga D, Sakamoto H, Matsuda K, Kurokawa M, Kawata M, Kubo T. Behavior of host and graft cells in the early remodeling process of rotator cuff defects in a transgenic animal model. *J Shoulder Elbow Surg* 2008;17(1 Suppl):101S–107S. [PubMed: 18162414]
10. Lin JL, Carreira D, Ponnappan R, Volz B, Cole BJ. Use of bipolar radiofrequency energy in delayed repair of acute supraspinatus tears in rats. *J Shoulder Elbow Surg* 2007;16(5):640–648. [PubMed: 17583540]
11. Murrell GA. Oxygen free radicals and tendon healing. *J Shoulder Elbow Surg* 2007;16(5 Suppl):S208–214. [PubMed: 17509903]
12. Szomor ZL, Appleyard RC, Murrell GA. Overexpression of nitric oxide synthases in tendon overuse. *J Orthop Res* 2006;24(1):80–86. [PubMed: 16419972]
13. Thomopoulos S, Williams GR, Soslowsky LJ. Tendon to bone healing: differences in biomechanical, structural, and compositional properties due to a range of activity levels. *J Biomech Eng* 2003;125(1):106–113. [PubMed: 12661203]
14. Zalavras CG, Gardocki R, Huang E, Stevanovic M, Hedman T, Tibone J. Reconstruction of large rotator cuff tendon defects with porcine small intestinal submucosa in an animal model. *J Shoulder Elbow Surg* 2006;15(2):224–231. [PubMed: 16517370]
15. Alaverdashvili M, Leblond H, Rossignol S, Whishaw IQ. Cineradiographic (video X-ray) analysis of skilled reaching in a single pellet reaching task provides insight into relative contribution of body, head, oral, and forelimb movement in rats. *Behav Brain Res* 2008;192(2):232–247. [PubMed: 18514337]
16. Childs JD, Sparto PJ, Fitzgerald GK, Bizzini M, Irrgang JJ. Alterations in lower extremity movement and muscle activation patterns in individuals with knee osteoarthritis. *Clin Biomech (Bristol, Avon)* 2004;19(1):44–49.
17. Clarke KA. Differential fore- and hindpaw force transmission in the walking rat. *Physiol Behav* 1995;58(3):415–419. [PubMed: 8587946]
18. Giszter SF, Davies MR, Graziani V. Coordination strategies for limb forces during weight-bearing locomotion in normal rats, and in rats spinalized as neonates. *Exp Brain Res* 2008;190(1):53–69. [PubMed: 18612631]
19. Kanagal SG, Muir GD. Bilateral dorsal funicular lesions alter sensorimotor behaviour in rats. *Exp Neurol* 2007;205(2):513–524. [PubMed: 17451687]
20. Kanagal SG, Muir GD. The differential effects of cervical and thoracic dorsal funiculus lesions in rats. *Behav Brain Res* 2008;187(2):379–386. [PubMed: 18037173]
21. Knoll Z, Kocsis L, Kiss RM. Gait patterns before and after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2004;12(1):7–14. [PubMed: 14586491]
22. Muir GD, Whishaw IQ. Complete locomotor recovery following corticospinal tract lesions: measurement of ground reaction forces during overground locomotion in rats. *Behav Brain Res* 1999;103(1):45–53. [PubMed: 10475163]
23. Muir GD, Whishaw IQ. Ground reaction forces in locomoting hemi-parkinsonian rats: a definitive test for impairments and compensations. *Exp Brain Res* 1999;126(3):307–314. [PubMed: 10382617]
24. Muir GD, Whishaw IQ. Red nucleus lesions impair overground locomotion in rats: a kinetic analysis. *Eur J Neurosci* 2000;12(3):1113–1122. [PubMed: 10762342]
25. Best TM, Collins A, Lilly EG, Seaber AV, Goldner R, Murrell GA. Achilles tendon healing: a correlation between functional and mechanical performance in the rat. *J Orthop Res* 1993;11(6):897–906. [PubMed: 8283336]
26. Davidson CJ, Ganion LR, Gehlsen GM, Verhoestra B, Roepke JE, Sevier TL. Rat tendon morphologic and functional changes resulting from soft tissue mobilization. *Med Sci Sports Exerc* 1997;29(3):313–319. [PubMed: 9139169]
27. Fu SC, Chan KM, Chan LS, Fong DT, Lui PY. The use of motion analysis to measure pain-related behaviour in a rat model of degenerative tendon injuries. *J Neurosci Methods* 2009;179(2):309–318. [PubMed: 19428542]
28. Messner K, Wei Y, Andersson B, Gillquist J, Rasanen T. Rat model of Achilles tendon disorder. A pilot study. *Cells Tissues Organs* 1999;165(1):30–39. [PubMed: 10460971]

29. Murrell GA, Lilly EG 3rd, Collins A, Seaber AV, Goldner RD, Best TM. Achilles tendon injuries: a comparison of surgical repair versus no repair in a rat model. *Foot Ankle* 1993;14(7):400–406. [PubMed: 8406260]
30. Perry SM, Getz CL, Soslowky LJ. Alterations in function after rotator cuff tears in an animal model. *J Shoulder Elbow Surg* 2009;18(2):296–304. [PubMed: 19218053]
31. Clarke KA, Parker AJ. A quantitative study of normal locomotion in the rat. *Physiol Behav* 1986;38(3):345–351. [PubMed: 3786515]
32. Giszter SF, Davies MR, Graziani V. Motor strategies used by rats spinalized at birth to maintain stance in response to imposed perturbations. *J Neurophysiol* 2007;97(4):2663–2675. [PubMed: 17287444]
33. Howard CS, Blakeney DC, Medige J, Moy OJ, Peimer CA. Functional assessment in the rat by ground reaction forces. *J Biomech* 2000;33(6):751–757. [PubMed: 10807997]
34. Thota AK, Watson SC, Knapp E, Thompson B, Jung R. Neuromechanical control of locomotion in the rat. *J Neurotrauma* 2005;22(4):442–465. [PubMed: 15853462]
35. Webb AA, Gowribai K, Muir GD. Fischer (F-344) rats have different morphology, sensorimotor and locomotor abilities compared to Lewis, Long-Evans, Sprague-Dawley and Wistar rats. *Behav Brain Res* 2003;144(1–2):143–156. [PubMed: 12946605]
36. Kanchiku T, Lynskey JV, Protas D, Abbas JJ, Jung R. Neuromuscular electrical stimulation induced forelimb movement in a rodent model. *J Neurosci Methods* 2008;167(2):317–326. [PubMed: 17870182]
37. Koopmans GC, Deumens R, Brook G, Gerver J, Honig WM, Hamers FP, Joosten EA. Strain and locomotor speed affect over-ground locomotion in intact rats. *Physiol Behav* 2007;92(5):993–1001. [PubMed: 17959205]
38. Fischer MS, Blickhan R. The tri-segmented limbs of therian mammals: kinematics, dynamics, and self-stabilization--a review. *J Exp Zool A Comp Exp Biol* 2006;305(11):935–952.

Figure 1.

Illustration of a rat walking in the instrumented confined walkway and associated coordinate system. Mirrors (only one shown for clarity) were placed along side the walkway such that a 60 (fps) camera, placed beneath the walkway, could capture both sagittal and ventral views of the animal as it walked across two force plates (6 DOF load-cells).

Figure 2. Step width and length defined as the difference in centroids of the left-forepaw (LF) and right-forepaw (RF) in the medial/lateral (x) and fore/aft (y) directions respectively.

Figure 3.

Typical ground reaction forces (x, y and z) versus time of the left-forelimb with maxima and minima of interest highlighted. Notice that force in the x-direction remains negative (lateral), that force in the y-direction is first negative (braking) and then positive (propulsion), and that force in the z-direction (vertical) is much larger than in the other two directions.

Table 1

Step width and step length (data as mean $\pm$ standard deviation) for control uninjured animals at day -1 were not significantly different between methods.

System	Width (mm)	Length (mm)
Instrument (n=8)	29.9 $\pm$ 3.7	68.8 $\pm$ 4.8
Paper (n=12)	28.3 $\pm$ 6.4	69.3 $\pm$ 7.9

Table 2

Ground reaction force data (mean $\pm$ standard deviation) for all limbs (left forelimb, left hindlimb, right forelimb, right hindlimb) of uninjured control data at day-1.

Parameter	LF	LH	RF	RH
Average (Fy) (%BW)	-1.7 ± 1.3	$^a1.6 \pm 1.3$	-1.6 ± 1.5	$^a2.5 \pm 0.6$
Peak Ventral (-Fz) (%BW)	49.0 ± 5.0	$^a57.7 \pm 4.5$	46.4 ± 5.1	$^a56.6 \pm 3.3$
Peak Lateral (Fx) (%BW)	4.4 ± 0.9	$^a6.4 \pm 1.7$	5.0 ± 1.3	$^a7.1 \pm 1.5$

^a denotes differences between fore and hind limbs.

Ambulatory parameters (mean $\pm$ standard deviation) for the left forelimb at all time points for both the repaired (REP) and uninjured (UNINJ) groups.

Table 3

Parameter	Group	Day-1	Day3	Day7	Day14	Day28	Day42	Day56
Speed (cm/sec)	REP	26.7 $\pm$ 7.1	22.6 $\pm$ 11.3	20.5 $\pm$ 6.1	26.9 $\pm$ 6.2	26.9 $\pm$ 7.0	25.1 $\pm$ 4.2	28.3 $\pm$ 5.7
Speed (cm/sec)	UNINJ	22.2 $\pm$ 5.6	23.9 $\pm$ 7.1	29.6 $\pm$ 9.7	26.2 $\pm$ 10.7	27.1 $\pm$ 5.4	27.6 $\pm$ 6.6	23.5 $\pm$ 6.7
Step Width (mm)	REP	31.8 $\pm$ 6.1	24.6 $\pm$ 7.0	28.3 $\pm$ 5.2	27.6 $\pm$ 6.5	27.3 $\pm$ 7.1	29.5 $\pm$ 4.8	28.2 $\pm$ 6.8
Step Width (mm)	UNINJ	29.9 $\pm$ 3.7	29.8 $\pm$ 4.2	29.3 $\pm$ 4.0	28.5 $\pm$ 5.0	33.1 $\pm$ 3.2	31.9 $\pm$ 6.3	32.8 $\pm$ 1.1
Step Length (mm)	REP	70.9 $\pm$ 7.2	* #42.6 $\pm$ 15.5	* #59.0 $\pm$ 9.0	70.3 $\pm$ 8.2	76.3 $\pm$ 8.0	#80.3 $\pm$ 6.1	81.4 $\pm$ 5.8
Step Length (mm)	UNINJ	68.8 $\pm$ 4.8	75.9 $\pm$ 5.8	#79.4 $\pm$ 6.4	78.6 $\pm$ 11.5	71.7 $\pm$ 7.4	#78.0 $\pm$ 4.6	74.7 $\pm$ 7.4
Fx-max (%BW)	REP	* 6.3 $\pm$ 1.6		* # 1.3 $\pm$ 1.0	4.1 $\pm$ 1.7	4.4 $\pm$ 1.8	4.4 $\pm$ 1.9	4.4 $\pm$ 1.8
Fx-max (%BW)	UNINJ	4.4 $\pm$ 0.9		5.5 $\pm$ 2.1	5.5 $\pm$ 1.2	5.1 $\pm$ 0.5	5.3 $\pm$ 2.8	3.8 $\pm$ 1.9
Fy-min (%BW)	REP	7.1 $\pm$ 2.2		* 1.6 $\pm$ 0.7	4.2 $\pm$ 3.9	6.1 $\pm$ 3.2	5.5 $\pm$ 3.7	5.0 $\pm$ 1.9
Fy-min (%BW)	UNINJ	7.4 $\pm$ 3.7		5.8 $\pm$ 2.6	8.0 $\pm$ 4.1	8.8 $\pm$ 2.4	7.4 $\pm$ 1.9	5.5 $\pm$ 1.6
Fy-max (%BW)	REP	5.4 $\pm$ 2.2		* 2.5 $\pm$ 1.5	4.8 $\pm$ 1.3	4.5 $\pm$ 0.8	4.9 $\pm$ 0.9	5.0 $\pm$ 1.3
Fy-max (%BW)	UNINJ	4.9 $\pm$ 2.3		5.5 $\pm$ 1.9	5.5 $\pm$ 2.0	4.2 $\pm$ 1.5	3.9 $\pm$ 2.0	4.2 $\pm$ 1.6
Fz-min (%BW)	REP	50.6 $\pm$ 5.6		* #24.6 $\pm$ 3.3	* 41.0 $\pm$ 8.4	46.9 $\pm$ 5.5	50.6 $\pm$ 5.8	52.0 $\pm$ 5.3
Fz-min (%BW)	UNINJ	49.0 $\pm$ 5.4		52.9 $\pm$ 3.0	55.4 $\pm$ 4.3	46.8 $\pm$ 4.3	48.4 $\pm$ 4.7	45.5 $\pm$ 4.5

* denotes significant differences between groups using a 1 tailed t-test $p < 0.05/6$, and

denotes significant difference from day-1 $p < 0.05/6$