



Center of pressure in a walking boot shifts posteriorly in patients following lower leg fracture

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ABSTRACT

Background: Studies have shown that the ambulatory behavior and amount of weight bearing performed by lower leg fracture patients, increases over time. It is likely that gait features, such as center of pressure (CoP), also change over time.

Research Question: The purpose of this study was to characterize changes in CoP exhibited by lower leg fracture patients wearing a walking boot during the recovery period.

Methods: Approximately 2 weeks post-surgery, seven lower leg fracture patients were fitted with a MaxTrax walking boot which was integrated with the Ambulatory Tibia Load Analysis System, an underfoot load monitoring system. Patients wore the walking boot for 2–12 weeks resulting in continuous load data during the recovery period. Ambulation was filtered from the raw data and daily average CoP values were calculated by averaging the CoP vectors from all steps in a given day.

Result: In general, the CoP vector varied in both the x and y directions during the initial stages of recovery but was more uniform during the later stages of healing. In 6/7 patients, the CoP in the y direction was closer to the forefoot during the initial stages of healing but shifted posteriorly as time post-surgery increased. The single patient that did not exhibit a posterior shift in CoP was also the only patient to develop a non-union. CoP in the x direction show a less clear trend. CoP in the x direction exhibited a medial shift in 5 patients and a lateral shift in 2 patients.

Significance: During lower leg fracture recovery in a walking boot, the CoP in the y direction shifts posteriorly as time post-surgery increases and CoP monitoring may become a useful tool to monitor individual patient healing progression.

1. Introduction

The mechanical forces experienced by recovering bone are a major factor in fracture healing [1,2]. To promote healing while reducing the risk of complications, clinicians routinely instruct patients to gradually increase the load placed on the injured limb while wearing a walking boot [3]. This load, along with measures of fracture stiffness and radiographs, can be used to assess healing [4].

Changes in limb loading during the healing period will likely alter gait characteristics such as center of pressure (CoP). Previously, healthy volunteers simulating the walking behavior of lower leg fracture patients demonstrated that the CoP vector in a walking boot terminates before the midfoot at reduced weight bearing, but reaches the forefoot at full weight bearing [5]. Actual patients may exhibit such a change

which may be an indication of healing.

Traditional care requires clinic visits and x-rays at numerous time points during the healing period [6] and nonunions develop in 5–20% of cases [7,8]. Continuous, out of clinic CoP monitoring could be utilized as an adjunctive measure of healing that can inform clinicians of fracture healing progression. This could result in fewer clinic visits and exposure to x-rays for patients that are healing normally or earlier interventions for patients that have complications. The goal of this study was to characterize CoP in lower leg fracture patients during the healing period using the Ambulatory Tibia Load Analysis System (ATLAS) integrated into a walking boot.

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2. Methods

2.1. Patients

This study was a retrospective analysis of data obtained from the ATLAS in lower leg fracture patients which was approved by the Institutional Review Board at the University of Utah. Selection criteria for the original study were: ≥ 18 years of age, lower leg fracture, non-polytrauma, spoke English, weighed between 45–113 kg s, lived within 161 km of the hospital. All patients provided informed consent. Patients who had at least 50% of their data from the boot use period successfully recorded were included in this analysis.

2.2. Study procedure

Approximately 2 weeks post-surgery, patients were instructed to wear a MaxTrax™ Air Walking Boot (DJO Global) instrumented with an ATLAS load-monitoring insole, custom made for each patient. The ATLAS contains three sensors: two under the forefoot and one under the heel [9]. Normal loads were measured from each sensor, sampled at 16 Hz and recorded onto a Secure Digital card. The ATLAS has an accuracy of ± 5%, minimal hysteresis and minimal static drift [10,11]. Patients were instructed to use crutches until they could fully weight bear and wear the boot at all times except when sleeping and during twice-daily active range of motion exercises. The duration of boot use was at the discretion of the clinician. When boot use was discontinued, the ATLAS insole was removed, and data were retrieved for analysis. Healing was assessed using radiographic measures.

2.3. Data analysis

Analysis was performed in MATLAB®. First, the raw data was filtered with an ambulation detection algorithm to obtain individual steps [12]. Next, CoP vectors for each step taken on a given day were calculated using established methods [5]:

$$CoP_x = \frac{\sum (x_i \times F_i)}{\sum F_i}$$

$$CoP_y = \frac{\sum (y_i \times F_i)}{\sum F_i}$$

CoP_x and CoP_y are across the width and length of the foot respectively. F_i is the force measured at each sensor and i (1–3) corresponds to sensors under the heel, medial forefoot and lateral forefoot. x_i and y_i are the normalized distances of each sensor from a reference point located medially and posteriorly to the ATLAS insole. The length of the insole was normalized to 10, to allow for CoP comparisons between patients. The CoP_x and CoP_y values from all steps taken in a given day were averaged, resulting in a daily average CoP_x and CoP_y.

3. Results

Patient characteristics and weight bearing protocols are shown in Table 1. Patients wore the ATLAS system for 2–12 weeks and the ATLAS sensors continuously collected data throughout the entirety of the boot use period for all patients, except patient 7. Due to an SD card error, data from days 59–89 were not captured. At the 6-month follow up visit, patients 1–6 were considered healed based upon radiographic measures while patient 7 was diagnosed with a non-union.

Examples of underfoot loads from the heel, lateral and medial sensors and their sum during a step are shown in Fig. 1a and b. The resulting CoP is shown in Fig. 1c and d. The load levels on each sensor on the 20th day post-surgery was lower than those on the 41st day post-surgery, representing the increase in percent body-weight loading throughout recovery.

The major trend observed was a posterior shift in the daily average

Table 1 Patient characteristics and post-surgical weight bearing protocols.

Patient Number	Age	Gender	Weight (kg)	Fracture Type ^a	Fixation Method	Weight Bearing Protocol Weeks 2-6	Weight Bearing Protocol Weeks 6-12	Linear Rate of Increase in Weight Bearing
1	24	Male	68	Diaphyseal Tibial Shaft Fracture	IM Rod	NWB	NA (WBAT in regular shoe)	.01% bodyweight/day
2	64	Female	67	Diaphyseal Tibial Shaft Fracture	IM Rod	WBAT	NA (WBAT in regular shoe)	1.79% bodyweight/day
3	29	Female	66	Diaphyseal Tibial Shaft Fracture	IM Rod and Lag Screws at Ankle	WBAT	WBAT	1.96% bodyweight/day
4	34	Female	93	Trans-syndesmoic Bimalleolar Ankle Fracture	ORIF plate and Screws	NWB	PWB at 25%	.04% bodyweight/day
5	21	Male	60	Diaphyseal Tibial Shaft Fracture	IM Rod	PWB at 25%	WBAT	1.57% bodyweight/day
6	24	Male	66	Diaphyseal Tibial Shaft Fracture	IM Rod	NWB	WBAT	1.39% bodyweight/day
7	39	Male	78	Diaphyseal Tibial Shaft Fracture	IM Rod and Lag Screws at Ankle	NWB	NA (PWB at 25%, data loss)	.06% bodyweight/day

NA, Not Applicable; WBAT, Weight Bearing as Tolerated; NWB, Non Weight Bearing; PWB, Partial Weight Bearing; IM, Intramedullary; ORIF, Open reduction and internal fixation.
^a The AO-Müller/Orthopaedic Trauma Association (AO/OTA) fracture and dislocation classification was used for identification of the fracture type.

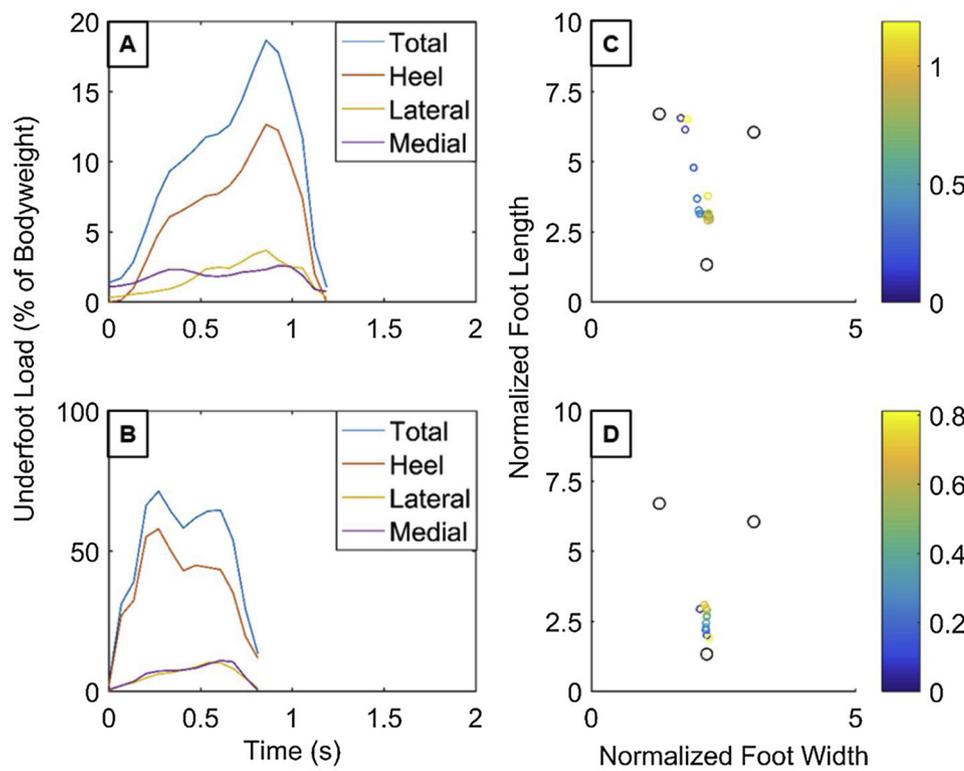


Fig. 1. Examples of weight bearing and CoP calculations. Underfoot load waveforms from a representative patient (Patient 6) on day (a) 21 and day (c) 40 post surgery. Data from the heel, medial, and lateral sensors and their sum are shown. The black circles represent the position of the sensors. The CoP from the initial stages of recovery (c) consists of a greater proportion of loading away from the heel near the midfoot, whereas the COP from a later timepoint (d) is near the heel and is more centered around the midpoint of the insole. The color of the dot represents the timepoint represented in the color-bar at the right side of the figure. Note that (d) differs from the COP in normal gait, without the use of a walking boot, where initial contact occurs at the heel and progresses through final contact at the great toe [5].

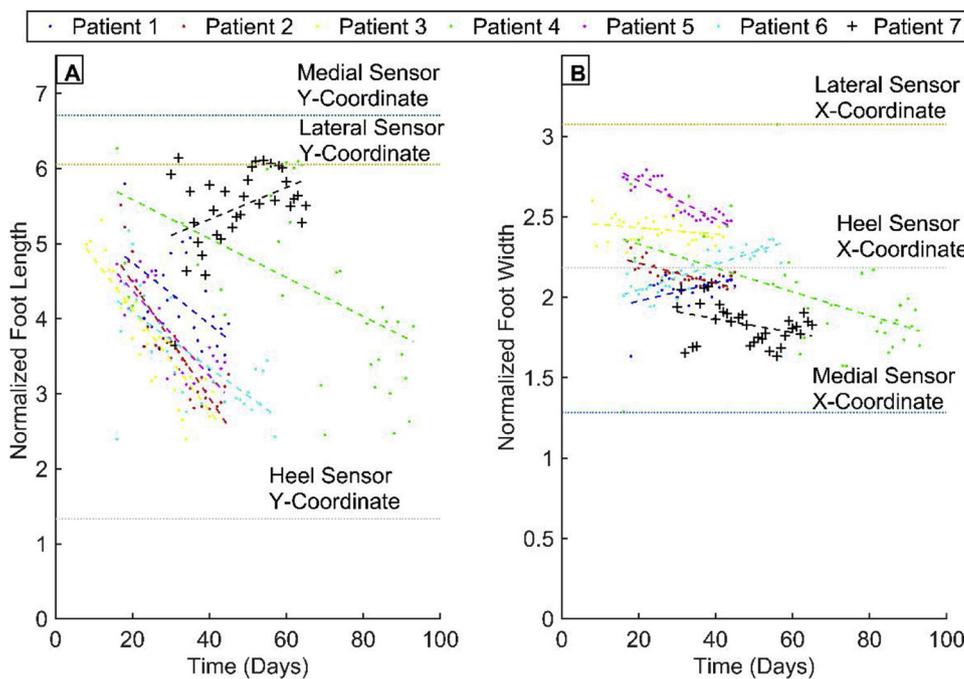


Fig. 2. The change over time in the position of the daily average CoPy and CoPx. (a) The daily average CoPy with the vertical position of the heel, medial, and lateral sensors is plotted for all patients. The average daily CoPy was initially closer to the forefoot than the heel but shifted posteriorly towards the heel sensor by day 40–42 for most patients (5/7). The only patients that had CoPy closer to the forefoot than the heel approximately 6 weeks post-surgery were patients 4 and 7. (b) The daily average CoPx with the horizontal position of the heel, medial, and lateral sensors is plotted for all patients. Compared to the CoPy there is a less of a clear trend over time. The CoPx shifted towards the medial side in 5 patients and towards the lateral side in 2 patients. The CoPx shifted across the midline (either medial to lateral or lateral to medial) in a subset of 3 patients.

CoPy from the forefoot towards the heel (Fig. 2a) in 6/7 patients. The daily average CoPy shifted approximately from the forefoot (days 16–23) to the heel (days 38–42) in 5 patients. A similar posterior shift occurred over a period of 90 days for patient 4. In contrast, the daily average CoPy shifted anteriorly and remained near the forefoot in patient 7. Additionally, the daily average CoPy was associated with a positive slope in patient 7, whereas all other patients had a negative slope. The CoPx data (Fig. 2b) did not show a noticeable trend. The daily average CoPx shifted towards the medial direction in patients 2,3,4,5,7 and towards the lateral direction in patients 1 and 6.

4. Discussion

This study evaluated the CoP in a walking boot in lower leg fracture patients during recovery. Our results indicated a posterior shift in the CoPy in all patients that healed within 6 months. During the first 4 weeks post-surgery, the load distribution during ambulation was primarily between the midfoot and the forefoot, away from the heel (Fig. 2a). As time post-surgery increased, the CoPy shifted posteriorly towards the heel. In contrast, a previous study with healthy volunteers indicated that CoPy shifted anteriorly as weight bearing increased [5]. This difference may be attributed to the different ways that partial

weight bearing is modulated between healthy, pain-free participants and actual recovering patients while wearing a walking boot. Studies of similar fractures also report increased pressures under the forefoot and decreased pressures under the heel during the recovery period [13–15]. However, a major limitation of these studies is that the data are obtained from experiments that only measure 5–20 steps inside of a clinic, without use of a walking boot. Our results, derived from continuous data outside of the clinic, provide a stronger representation of patient behavior. Compared to the other patients, patients 4 and 7 did not exhibit a posterior shift in CoP_y by day 42. Interestingly, these two patients were prescribed the longest duration of a restrictive weight bearing protocol. Patient 7, who developed a non-union, exhibited an anterior shift in CoP_y with a positive slope. Although patient 4 did not initially show posterior shift in CoP_y , continued use of the walking boot revealed a delayed posterior shift (by day 90), similar to the other patients that healed.

Limitations of this study include a lack of compliance measurement, segments of missing data and a small sample size. Despite these limitations, the data indicate that CoP_y shifts posteriorly in patients that heal. Future studies are needed to determine a correlation between CoP vectors and healing. Continuous CoP monitoring may become a useful measure for clinicians to gain insights into individual patient's progression during recovery.

Conflict of interest statement

There are two potential conflicts of interest. The first is with co-author Dr. Bamberg and her association with a University of Utah startup, Veristride, which has an option to license the ATLAS technology. The second is that the coauthors Erik Kubiak, Tomasz Petelenz, and Robert Hitchcock have patents related to the load monitoring technology described in this manuscript.

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