Plantar Pressure and Gait Symmetry in Individuals with Fractures versus Tendon Injuries to the Hindfoot

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Background: The intent of this study was to determine whether differences in function, walking characteristics, and plantar pressures exist in individuals after operative fixation of an intra-articular calcaneal fracture (HFX) compared with individuals with operative repair of an Achilles tendon rupture (ATR).

Methods: Twenty patients (ten with HFXs and ten with ATRs) were recruited approximately 3.5 months after operative intervention. All of the participants completed the Lower Extremity Functional Scale and had their foot posture assessed using the Foot Posture Index. Walking velocity was assessed using a pressure mat system, and plantar pressures were measured using an in-shoe sensor. In addition to between-group comparisons, the involved foot was compared with the uninvolved foot for each participant.

Results: There were no differences in age, height, weight, or number of days since surgery between the two groups. The HFX group had lower Lower Extremity Functional Scale scores, slower walking velocities, and different forefoot loading patterns compared with the ATR group. The involved limb of both groups was less pronated.

Conclusions: The results indicate that individuals with an HFX spend more time on their involved limb and walk slower than those with an ATR. Plantar pressures in the HFX group were higher in the lateral forefoot and lower in the medial forefoot and in the ATR group were symmetrically lower in the forefoot. (J Am Podiatr Med Assoc 105(6): 469-477, 2015)

Traumatic injuries to the hindfoot, including intra-articular calcaneal fractures (HFXs) and Achilles tendon ruptures (ATRs), can lead to a highly variable course of recovery and result in considerable loss of function. Thus, an understanding of the variations in the level of function and characteristics of how the foot is loaded early in the recovery process can be invaluable for planning an effective rehabilitation program.

Intra-articular fractures to the calcaneus are usually the result of falls from a height or motor vehicle trauma and often lead to long-term decreases in functional abilities compared with preinjury levels.1-3 After operative repair, these fractures can result in difficulty returning to previous work-related activities and additional costly operative procedures.1,3,4 Individuals who sustain HFXs must often deal with long-term range-of-motion limitations and post-traumatic osteoarthritis that can eventually lead to fusions of the subtalar joint.1,4,5 Previous studies assessing plantar pressure patterns and temporal characteristics during walking in individuals with HFXs have reported that contact time is reduced on the involved side compared with the uninvolved side and that, in most cases, plantar pressures are significantly increased in the lateral forefoot. Rosenbaum et al6 studied 14 patients, two-thirds of whom were managed surgically, using a pressure sensor platform to assess dynamic plantar pressures. They reported not only that forces were reduced on the injured foot versus the noninjured foot but also that peak plantar pressures were...
significantly decreased in the medial forefoot and significantly increased in the lateral forefoot. The patients in that study were all assessed 4 years after surgery. Schepers et al7 also used a pressure platform to assess 21 individuals with unilateral HFXs 1.5 years after operative repair. Similar to the results of the study by Rosenbaum et al,6 they reported that forces were reduced on the injured foot compared with the noninjured foot. In contrast to the study by Rosenbaum et al, however, Schepers et al found that maximum plantar pressures were increased under the medial forefoot region of the involved extremity. In a more recent study, Hirschmuller et al8 assessed plantar pressures and several gait parameters in 60 individuals 1 year after surgery to repair a unilateral HFX. Using a pressure sensor platform for data collection, they reported a shorter contact period during walking on the injured side, with increased peak plantar pressures in the midfoot and lateral forefoot regions.

Although the Achilles tendon is the strongest and thickest tendon in the human body, it is the most commonly ruptured tendon, and the incidence is increasing.9 Achilles tendon repairs account for 40% of all operative tendon repairs.9 Although the incidence of ATRs ranges from 11.3 to 37.7 per 100,000,10,11 few studies have assessed plantar pressure or temporal characteristics of walking after operative repair of an ATR. Chan et al12 assessed 19 individuals who had undergone an operative repair of the Achilles tendon 6 to 62 months after injury and reported that step length and stance phase duration were similar between the injured and noninjured extremities. In a more recent study, Mezzarobba et al13 reported no differences between extremities in step length, step duration, or gait speed in 21 individuals with an ATR 2 years after surgery. They also reported that the ATR repair group exhibited a reduction in force during the propulsion phase of walking and a decrease in forefoot plantar pressures measured using a specially designed baropodometric platform.

Operative repair of HFXs and ATRs in most cases involves a period of nonweightbearing. After the period of nonweightbearing, both groups of patients are often immobilized in a walking boot for 10 to 12 weeks. After Achilles tendon repair, patients are often initially placed in a walking boot with the foot plantarflexed to avoid tendon elongation, which would result in functional deficit.11,14 This period of immobilization for both groups often leads to joint stiffness, difficulties with gait, and a decreased level of function once the patient is allowed to begin walking without the walking boot.

Although the assessment of plantar pressures and various temporal characteristics of walking can provide valuable information on the loading patterns and weight acceptance on the injured and noninjured feet, patient self-reported outcome instruments also play an important role in determining the patient’s functional status. The Lower Extremity Functional Scale (LEFS) consists of 20 items (each with a maximum score of 4) and has been shown to be a reliable and valid measure of documenting lower-extremity function.15 Binkley et al15 administered the LEFS to 107 patients with lower-extremity musculoskeletal dysfunction and reported that the sensitivity to change of the LEFS was superior to that of the SF-36 and that the minimal clinically important difference was 9 scale points. In a more recent study, Yeung et al16 used the LEFS to assess functional performance in 142 inpatients in an orthopedic rehabilitation ward. They also concluded that the LEFS was a reliable and valid tool to assess group and individual changes in function with high levels of responsiveness.

In previous studies focused on assessing plantar pressure and temporal characteristics in individuals who have had either an HFX or an ATR, the length of time between the operative repair and the assessment has ranged from 1 to 5 years. Although waiting to assess the effectiveness of surgery and rehabilitation after this length of time can provide important information regarding long-term outcomes, assessing various parameters after this length of time does not permit the modification of rehabilitation programs or the implementation of early orthotic device/footwear interventions that could improve those long-term outcomes. In addition, previous studies assessing plantar pressure patterns have used platform systems to collect data. Whereas platform systems offer the advantage of having higher resolution due to a greater number of sensors, a major disadvantage is that pressure data can be collected only from a single foot contact, which requires multiple walking trials. In addition, another factor that can affect pressure data collection using a platform system is termed targeting. Targeting refers to patients altering their walking pattern so that they can ensure that their foot makes contact with the platform.17 The use of a pressure sensor insole placed inside the patient’s shoe eliminates the problem of targeting. In addition, in-shoe pressure data collection provides the clinician with information about the pressures occurring in the shoe at the shoe-foot interface.

To our knowledge, no studies have compared the
differences in temporal characteristics of walking or plantar pressure patterns in individuals who have had operative fixation of an HFX compared with individuals with an operatively repaired ATR at the end of 12 weeks of immobilization in a walking boot. The purpose of this study was to determine whether differences exist in functional levels, temporal characteristics, and plantar pressure patterns during walking in individuals who have had surgical fixation of an HFX compared with those who have undergone surgical repair of an ATR. We developed three hypotheses for this study. First, we hypothesized that patients undergoing HFX surgical fixation are more likely to report lower LEFS scores and have a less pronated foot posture on the involved side compared with those who have undergone an ATR repair. Second, we hypothesized that individuals who have undergone operative fixation after HFX demonstrate slower gait velocity and shorter stance phase duration on the involved side compared with those who have undergone an ATR. Finally, we hypothesized that mean maximum pressures after HFX are decreased in the medial and lateral forefoot regions compared with the ATR group and that medial and lateral forefoot pressures are lower in the involved extremity than in the uninvolved extremity for both groups.

**Methods**

**Participants**

Twenty individuals were recruited to participate in this study from a pool of patients who were referred for physical therapy after either an open reduction and internal fixation of a unilateral HFX with or without a subtalar joint fusion (nine men and one woman) or an ATR with a subsequent surgical repair (ten men). Prospective participants were approached by the principal investigator (S.R.A.) and were asked to participate in the study. All of the patients were recruited for participation in this study approximately 3.5 months after operative intervention and at the end of 12 weeks of immobilization in a walking boot. None of the participants received any type of rehabilitation during the 12-week immobilization period or between the time they stopped using the walking boot and started participation in the study. None of the participants had any other significant injury that would otherwise affect his or her ability to walk and bear weight on his or her extremities. This study was approved by the Intermountain Healthcare Institutional Review Board, and all of the participants read and signed an informed consent form before data collection.

**Instrumentation**

Pressure sensor insoles (Novel Electronics Inc, St. Paul, Minnesota) consisting of a matrix of 90 to 100 capacitance transducers approximately 2 mm thick with a sampling rate of 50 Hz were used to record the pressure data in the shoe. The pressure sensor insole was attached to the PEDAR portable insole system (Novel Electronics Inc), which transmitted data to a laptop computer using Bluetooth wireless technology. The five pairs of different-sized insoles used in this study were each calibrated before the start of data collection by means of a rubber bladder that was pressurized with compressed air. The calibration procedure consisted of applying a linear range of pressures to each insole from 0 to 600 kPa. The input pressure saturation value for each capacitance sensor was 700 kPa. In the present study, none of the patient trials achieved pressure saturation during data collection. To permit standardization of footwear during testing, the pressure sensor insoles were placed in martial arts shoes (testing footwear) that had a soft leather upper and a hard rubber outsole (Tiger Claw martial artist’s athletic shoes; Pioneer Interstate Inc, Nashville, Tennessee).

**Procedures**

The height and weight of each participant were recorded, and then the participants were asked to complete the LEFS. Participants were then asked to march in place for at least 5 sec and stop in a comfortable relaxed standing position with their weight distributed equally on both feet. With the patient standing in this position with both arms at the side and looking straight ahead, the Foot Posture Index (FPI) was performed. The FPI is a measure of a person’s resting standing foot posture, and it is composed of six items\textsuperscript{18}: talar head palpation, curves above and below the lateral malleoli, calcaneal angle, talonavicular bulge, medial longitudinal arch, and forefoot abduction/adduction. Each item of the FPI is scored on a 5-point scale from –2 to +2, with a sum total of all items of –12 to +12. Negative values represent a supinated posture, and positive values represent a pronated posture. The FPI was performed on all of the patients by the same investigator (S.R.A.) and has been shown to be a reliable method to assess foot posture.\textsuperscript{19-21} The FPI has also been shown to be correlated to static measures of foot mobility.\textsuperscript{22}
When assessment of the FPI was completed, each participant was seated and fitted with a pressure sensor insole of the appropriate size. The pressure sensor was then placed in the testing footwear, and the participant was asked to stand and perform two practice walks along the 8-m GAITRite mat system (CIR Systems Inc, Sparta, New Jersey). Once the participant had acclimated to the test condition, he or she was asked to walk twice over the GAITRite mat system so that gait velocity, stance phase duration times, and in-shoe pressure data could be recorded. The FPI and the plantar pressure assessment were performed on both feet for each participant, and none of the participants required use of an assistive device during any of the data collection sessions.

Data Analysis

The EMED Pedar expert software (Novel Electronics Inc) was used to select five left and five right steps from each of the two walking trials, for a total of ten steps for each extremity. The ten steps were selected from the middle 4.6-m section of the 8-m walk to ensure that the participants were neither accelerating nor decelerating from their self-selected walking speed. The number of steps selected for analysis was based on the work of Kernozek et al, who reported that a minimum of three to six consecutive steps were needed to achieve a level of reliability greater than 0.90 using the EMED Pedar system. The Novel Multimask software (Novel Electronics Inc) was used to divide the foot into the following five regions: heel, midfoot, medial forefoot, lateral forefoot, and hallux. These regions were based on a percentage of the total foot length and width and were consistently applied to each patient’s footprint. The heel region was from 0% to 30%, and the midfoot region was from 30% to 60% of total foot length. The forefoot region was from 60% to 80%, and the hallux and toes were from 80% to 100% of the total foot length. The forefoot region was further divided into equal halves, and the hallux was defined as the medial 35% of the hallux/toe region (Fig. 1). Once the five regions for each step were defined, the mean maximum pressure was calculated for each of the five regions. In addition, the stance phase duration was calculated for each step and then was averaged for the ten steps of each extremity.

Statistical Analysis

In addition to descriptive statistics, inferential statistical tests were performed. A series of independent \( t \) tests were performed to determine whether the two groups of patients were significantly different on any of the demographic characteristics, walking velocity, or LEFS score. Because the 5-point scale used to calculate FPI scores is considered to be ordinal data, it was necessary to convert the original FPI scores to interval data to perform statistical analyses. The Rasch transformation model described by Keenan et al was used to convert the original FPI ordinal scores to interval scores, with the transformed FPI interval scores used in subsequent analyses. A series of two-way analysis of variance (ANOVA) tests was performed on the transformed FPI scores to determine whether individuals in the HFX group were significantly different from those in the ATR group and whether the involved extremity was significantly different from the uninvolved extremity. The two-way ANOVA tests were also used to determine whether there was a significant interaction between the two groups and the two extremities. Finally, a series of two-way ANOVA tests were performed on the mean maximum pressure values for each plantar region. All decisions regarding statistical significance were made using a \( P \) value of 0.05.

Results

The mean age, height, and weight of the study groups are given in Table 1. No significant differences (\( P > .05 \)) were observed between the two
The mean weight (13.5) was significantly (6) the ATR group (56.9). Time since surgery (d) was 106.2 ± 17.7 for the involved extremity and 117.6 ± 31.8 for the uninvolved extremity. The mean stature was 6.0.6.0.4. The mean gait velocity for the HFX group was 0.61 ± 0.23 m/s and for the ATR group was 0.63 ± 0.26 m/s. The mean stance durations for each group and for the involved and uninvolved extremities for the two groups are shown in Table 2. For the lateral foot region, mean maximum plantar pressure was found to be significantly (P = .028) lower in the HFX group compared with the ATR group. In addition, the lateral foot region mean maximum plantar pressure for the involved extremity was significantly (P = .000) less than that for the uninvolved extremity, regardless of group membership. Finally, there was no significant (P = .716) interaction between the groups and the extremities (Table 3 and Fig. 2).

The mean maximum plantar pressure values for the two groups and each extremity in each of the plantar regions are shown in Table 3 and Fig. 2. The two-way ANOVA test showed that there was no significant difference between the two groups (P = .562) or between the two extremities (P = .180) for the heel region. In addition, there was no significant (P = .062) interaction between the groups and the extremities for the heel region.

For the midfoot region, mean maximum plantar pressure was found to be significantly (P = .031) less in the HFX group compared with the ATR group. In addition, the midfoot region mean maximum plantar pressure for the involved extremity was significantly (P = .000) less than that for the uninvolved extremity, regardless of group membership. Finally, there was no significant (P = .716) interaction between the groups and the extremities (Table 3 and Fig. 2). For the lateral foot region, mean maximum plantar pressure was found to be significantly (P = .027) less in the HFX group compared with the ATR group. In addition, the lateral foot region mean maximum plantar pressure for the involved extremity was significantly (P = .002) less than that for the uninvolved extremity, regardless of group membership. Finally, there was no significant interaction (P = .965) between the two groups and the two extremities (Table 3 and Fig. 2).

To help further understand the loading of the medial and lateral foot in each of the two groups, a series of correlated t tests was performed to determine whether the mean maximum pressure in

<table>
<thead>
<tr>
<th>Table 1. Demographic Characteristics of the 20 Study Participants by Group</th>
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<tr>
<td>Characteristic</td>
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</tr>
<tr>
<td>Age (years)</td>
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<tr>
<td>Height (cm)</td>
</tr>
<tr>
<td>Weight (kg)</td>
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<tr>
<td>Time since surgery (d)</td>
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</tbody>
</table>

Note: Data are given as mean ± SD.

<table>
<thead>
<tr>
<th>Table 2. Stance Duration and Foot Posture Index Values by Group and Extremity</th>
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<tbody>
<tr>
<td>Variable</td>
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<tr>
<td></td>
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<tr>
<td>Stance duration (sec)</td>
</tr>
<tr>
<td>Foot Posture Index (transformed)</td>
</tr>
</tbody>
</table>

Note: Data are given as mean ± SD.
the medial forefoot was different from that in the lateral forefoot. The results of those tests showed that the maximum pressure in the medial forefoot was significantly ($P = .017$) less than that in the lateral forefoot for the involved extremity of the HFX group but not the ATR group ($P = .205$). Furthermore, the maximum pressure in the medial and lateral forefoot regions was not significant for the involved ($P = .911$) or the uninvolved ($P = .197$) extremity.

For the hallux region, mean maximum plantar pressure was found to be significantly ($P = .027$) less in the HFX group compared with the ATR group. In addition, the mean maximum plantar pressure for the involved extremity was significantly ($P = .018$) less than that for the uninvolved extremity, regardless of group membership. Finally, there was a significant ($P = .004$) interaction between groups and extremities, indicating that the difference between the involved and uninvolved extremities was greater in the HFX group compared with the ATR group (Table 3 and Fig. 2).

### Discussion

The intent of this study was to determine the differences in functional levels, temporal characteristics, and plantar pressure patterns during walking for individuals who have had operative fixation of an HFX compared with those who have undergone an ATR repair. Based on the findings of previously published studies that had investigated either HFX or ATR, we developed three hypotheses. We hypothesized those individuals undergoing operative fixation of an HFX are more likely to report lower LEFS scores and have a less pronated foot posture on the involved side compared with those who have undergone ATR. Our rationale for this hypothesis was that individuals with an HFX would have significantly greater loss of hindfoot range of motion on the involved side compared with those with an ATR, leading to a lower level of function and a loss of foot mobility. Based on the results of this study, the mean LEFS score for the HFX group was statistically significantly lower than that for the ATR group. The transformed FPI scores were also lower for the involved side compared with the noninvolved side, irrespective of the group. Thus, while the level of function for the HFX group was lower than that for the ATR group, the involved foot for both groups was significantly less pronated than the noninvolved foot. Although we did not assess foot mobility in this study, because the FPI has previously been shown to be correlated with foot mobility, one could speculate that the amount of mobility of the involved foot for both groups was also decreased. The difference in the LEFS score between the HFX and ATR groups in the present study was 15.7 points. The minimal clinically important difference for the LEFS score is 9

### Table 3. Maximum Plantar Pressures by Group and Extremity for the Five Plantar Regions Studied

<table>
<thead>
<tr>
<th>Region</th>
<th>Intra-articular Calcaneal Fracture</th>
<th>Achilles Tendon Rupture</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Involved Extremity</td>
<td>Uninvolved Extremity</td>
</tr>
<tr>
<td>Heel</td>
<td>125.6 ± 51.8</td>
<td>110.2 ± 25.4</td>
</tr>
<tr>
<td>Midfoot</td>
<td>62.8 ± 20.0</td>
<td>61.5 ± 18.0</td>
</tr>
<tr>
<td>Medial forefoot</td>
<td>47.6 ± 28.9</td>
<td>108.4 ± 23.6</td>
</tr>
<tr>
<td>Lateral forefoot</td>
<td>66.4 ± 29.0</td>
<td>103.0 ± 19.3</td>
</tr>
<tr>
<td>Hallux</td>
<td>31.0 ± 22.9</td>
<td>70.8 ± 21.8</td>
</tr>
</tbody>
</table>

![Figure 2. Mean maximum plantar pressures in each of the five plantar regions of the foot for the intra-articular calcaneal fracture (HFX) and Achilles tendon rupture (ATR) groups.](attachment:image.png)
The results of the present study show that there was no difference in the mean maximum pressure for the heel region between the involved and noninvolved feet or between the HFX and ATR groups. In the midfoot region, although there was no difference in mean maximum pressure between the involved and noninvolved feet for either the HFX or the ATR group, midfoot pressure was lower for the involved foot than on the noninvolved foot. There was no difference in the time spent on the involved versus the uninvolved foot for the ATR group. The slower gait velocity and the lack of symmetry in contact time between the involved versus uninvolved foot not only is in agreement with the previous research findings but also provides further evidence to support the reduction in the functional levels in the HFX group.8 The results of the present study regarding step duration and gait speed after ATR, however, are in contrast to the previous literature, indicating that there were no differences between the involved and uninvolved extremities.12,13 This observed difference could be related to the fact that the present study involved patients approximately 3.5 months after surgery, whereas the other studies looked at individuals 6 or more months after surgery. As such, it is possible that walking speed and stance phase duration eventually equilibrate after rehabilitation in individuals who have ruptured the Achilles tendon.

The results of the present study show that there was no difference in the mean maximum pressure for the heel region between the involved and noninvolved feet or between the HFX and ATR groups. In the midfoot region, although there was no difference in mean maximum pressure between the involved and noninvolved feet for either the HFX or the ATR group, midfoot pressure was lower in the HFX group compared with the ATR group.

As previously discussed, two of the three previous studies that have assessed plantar pressures in individuals after operative fixation of an HFX reported decreased peak plantar pressures in the medial forefoot and increased pressures in the lateral forefoot.6,8 The results of the present study support the previously published literature for the involved extremity but not the uninvolved extremity. Medial and lateral forefoot pressures for the HFX group were significantly less than those for the ATR group, with pressure values for the involved foot also significantly less than those for the noninvolved foot for both groups. Mean maximum pressures were 28% higher in the lateral forefoot compared with the medial forefoot for the HFX group.

In the only study to assess pressures in individuals with an operatively repaired ATR, Mezzarobba et al13 reported a decrease in forefoot pressures. The results of the present study show that medial and lateral forefoot pressures were statistically significantly higher in the AFR group compared with the HFX group. In addition, there was no difference between the medial and lateral forefoot regions, regardless of the extremity examined.

As expected, the forefoot pressures were significantly lower in the medial and lateral forefoot regions for the involved foot compared with the noninvolved foot of the ATR group. The forefoot pressures in the involved foot for the ATR group were almost identical: the medial forefoot pressure was 83.0 kPa and the lateral forefoot pressure was 84.6 kPa (Table 3 and Fig. 2). The findings in the hallux were similar to those in the forefoot region in that maximum plantar pressure was less in the HFX group compared with the ATR group. These findings support the third hypothesis that the HFX group has decreased pressures in the medial forefoot region and increased pressures in the lateral forefoot region, whereas the ATR group has a symmetrical pressure reduction in both forefoot regions.

The fact that lateral forefoot pressures were increased while medial forefoot and halluc pressures were decreased in the HFX group supports the previous findings of Rosenbaum et al6 and Hirschmuller et al8 that after open reduction and internal fixation for an HFX, individuals adopt a more lateral loading pattern when walking. This is further supported by the findings of Jansen et al,25 who showed that after HFX, individuals had lateralization of their gait line during walking. The fact that this seems to begin so early in the rehabilitation process (3.5 months after the surgical intervention) supports the need to use interventions, including manual therapy, foot orthotic devices, and footwear modifications, in an attempt to facilitate greater loading of the medial foot.

The reduction in mean maximum plantar pressures in the medial and lateral forefoot regions of the involved foot of the HFX and ATR groups also indicates that the propulsion phase is reduced in these individuals, most likely secondary to calf muscle weakness and a lack of foot mobility. These
findings are in agreement with those reported by Mezzarobba et al., who assessed individuals 2 years after an ATR operative repair. In addition to the small number of participants being a limitation of the present study, data collection occurred over a shorter period and occurred soon after the patients were allowed to begin using a walking boot. In contrast, previous studies have focused on assessing plantar pressure and temporal gait characteristics in individuals after HFX or ATR 1 to 5 years after operative intervention. Although waiting to assess the effectiveness of surgery and rehabilitation for this extended period can provide important information regarding long-term outcomes, an important goal of this study was to assess foot posture, walking speed, and plantar pressure in the early stages of the rehabilitation program. Assessment of these variables early in the rehabilitation process is critical for selecting the most effective conservative interventions, including manual therapy, foot orthoses, and footwear. Although further research is always necessary, in our opinion, the use of these conservative interventions can have a major effect on the patient’s long-term outcomes.

Conclusions

The results of this study indicate that after operative repair of an HFX, individuals spend less time on the involved limb than on the noninvolved limb and have decreased gait velocity compared with individuals with an operatively repaired ATR. The HFX repair group also had a lower level of function 3.5 months after surgery compared with those with an ATR. As noted in previous studies, the HFX repair group applied less pressure to the medial forefoot and hallux with increased pressure to the lateral forefoot, whereas the ATR repair group had a symmetrical reduction of pressure in both regions of the forefoot. Finally, for both groups, the involved foot was found to be less pronated compared with the uninvolved extremity. Based on the findings of this study, clinicians should structure a rehabilitation and gait training program differently for patients who have undergone operative fixation for HFXs versus operative repair of the Achilles tendon. Making such decisions early in the rehabilitation process should ultimately reduce the patient’s impairments and maximize function after surgical intervention.

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Conflict of Interest: None reported.

References


