An investigation into the hammer toe effects on the lower extremity mechanics and plantar fascia tension: A case for a vicious cycle and progressive damage.

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Abstract

Hammer toes are one of the common deformities of the forefoot that can lead to compensatory changes during walking in individuals with this condition. Predicting the adverse effects of tissue damage on the performance of other limbs is very important in the prevention of progressive damage. Finite element (FE) and musculoskeletal modeling can be helpful by allowing such effects to be studied in a way where the internal stresses in the tissue could be investigated. Hence, this study aims to investigate the effects of the hammer toe deformity on the lower extremity, especially on the plantar fascia functions. To compare the joint reactions of the hammer toe foot (HTF) and healthy foot (HF), two musculoskeletal models (MSM) of the feet of a healthy individual and that of a participant with hammer toe foot were developed based on gait analysis. A previously validated 3D finite element model which was constructed using Magnetic Resonance Imaging (MRI) of the diabetic participant with the hammer toe deformity was processed at five different events during the stance phase of gait.

It was found that the hammer toe deformity makes dorsiflexion of the toes and the windlass mechanism less effective during walking. Specifically, the FE analysis results showed that plantar fascia (PF) in HTF compared to HF played a less dominant role in load bearing with both medial and lateral parts of PF loaded. Also, the results indicated that the stored elastic energy in PF was less in HTF than the HF, which can indicate a higher metabolic cost during walking. Internal stress distribution shows that the majority of ground reaction forces are transmitted through the lateral metatarsals in hammer toe foot, and the probability of fifth metatarsal fracture and also progressive deformity was subsequently increased. The MSM results showed that the joint reaction forces and moments in the hammer toe foot have deviated from normal, where the metatarsophalangeal joint reactions in the hammer toe were less than the values in the healthy foot. This can indicate a vicious cycle of foot deformity, leading to changes in body weight force transmission line, and deviation of joint reactions and plantar fascia function from normal. These in turn lead to increased internal stress concentration, which in turn lead to further foot deformities. This vicious cycle cause progressive damage and can lead to an increase in the risk of ulceration in the diabetic foot.

Keywords

Plantar fascia, Hammer toe, Finite element analysis, Plantar soft tissue, Diabetic foot ulcer

1. Introduction

The human body is a complicated mechanism with so many components where a compromised function in one section might impact other parts and cause the entire mechanism to deteriorate. Lower extremity health

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is a critical aspect of overall life quality that is influenced by various factors, including age, weight, musculoskeletal disorders, daily activities, and footwear [1–6]. Some of the common techniques that can be used to obtain appropriate information about the various internal tissues and elements functions are musculoskeletal and finite element modeling [7–10], gait analysis [11,12], and in-Vivo tests [13–16]. These techniques' data cause better identification of biomechanical body parameters, especially in the lower extremity.

The limbs' function has always been a top focus in biomechanics and in patients with diabetes to avoid injury, particularly in the foot. Diabetic ulceration has been widely studied in previous research [17–20], which shows that this issue is more important for diabetics. Excessive mechanical forces are one of the causes of foot ulcers [21,22]. Foot deformities can change the force distribution in components of the foot such as the plantar and bones and also can be the starting point for progressive damage such as foot ulcers [23–25]. Some injuries and damages in one area cause problems in another. Several investigations have been carried out to determine whether injury and deformities in one portion of the foot might cause problems in other parts of the body, such as the ankle, knee, and hip. In these studies, the effect of flat foot [26–28], hallux [29–31], and foot arch [32–34] on other parts of the lower limb were investigated. The plantar fascia and joints are the significant elements of the locomotor organs. Hence, forces and moments of the joints have been regarded as important factors in several types of research on joints [35–40].

Previous research looked into Plantar Fascia (PF) function and disorders [41,42]. The PF is a thick band of connective tissue that crosses the bottom of the foot, extending from the calcaneus to the base of the toes. PF plays important roles in foot arch support, stress distribution (load-sharing), energy storage, and shock absorption during walking [43]. PF stores elastic energy during the first half of the stance phase and some of this stored energy returns to the foot when the longitudinal arch recoils at the late stance phase which brings some of the mechanical energy required to enhance propulsion [44,45]. Stretched plantar fascia adds stiffness to the medial and lateral arch leading to an increase in the arch height whereby the lower leg muscles (soleus, medial and lateral gastrocnemius) can create plantarflexion moment to propel the body forward [46,47]. This is reinforced by the windlass mechanism, that is based on the shortening of the plantar fascia due to hallux dorsiflexion [48,49].

The hammer toe is one of the foot deformities in diabetes. The area involved in this deformity is the proximal interphalangeal joint, bent downward, and the toes deviate from being aligned to the metatarsals during rest and unloading situations. This abnormality occurs between 2 and 20% of all toe deformities [50]. Despite various reports about the association of some foot deformities with plantar pressure [51–53] and also relationship between plantar fascia and foot function, there has not been a full investigation of the effect of hammer toe deformity on the joints, PF, and overall progressive function. The aim of this study is to indicate some of the hammer toe side effects on the lower limb, especially in PF, during walking using finite element and musculoskeletal modeling which emerge from comparing the outcomes of healthy with hammer toe foot.

2. Method

2.1 Participants

The study was conducted according to the guidelines of the Endocrinology and Metabolism Research Institute and approved by the Institutional Review Board of the Amirkabir University of Technology, (98/11/33/80). The first participant was a male (age: 53, height: 165 cm, weight:93 Kg) with hammer toes deformity in the left foot and with no deformity at the contralateral foot (right foot). The second participant was a healthy female (age: 25, height: 163 cm, weight:58 Kg, Shoe size: 38) with no foot abnormalities who volunteered for the study. Both participants were recruited for gait analysis, and MRI imaging was done only on the first participant's left foot.

2.2 Gait analysis

Three-dimensional gait analysis was performed on both participants. 24 markers based on Vicon plug-in gait placement recommendations [54] and 14 extra markers as a modified plug-in gait were used [55–58]. The laboratory was equipped with 10 infrared cameras motion capture system (Vicon, Oxford, UK) with a data collection frequency of 100 Hz. For collecting ground reaction forces (GRFs) and centre of pressure (COP), two force plates (Kistler, Winterthur, Switzerland) sampled data at 1000 Hz. For collecting the foot plantar pressure distribution, a pressure pad system (Payatek, Tehran, Iran) was employed. The electromyography (EMG) system was a 6-channel wireless Myon product (Schwarzenberg, Switzerland) used in line with SENIAM guidelines [59,60]. Nexus software (Vicon, Oxford, UK) was used for collecting kinematic data (marker trajectories), muscle activation signals, GRFs, and COP in synchronization. Muscle activation was obtained from six major muscles: lateral gastrocnemius, tibialis anterior, soleus, medial gastrocnemius, tibialis posterior, and peroneus longus. To use the EMG data, a five-step procedure consisting of some filters and math operations were used. First the non-recursive fifth-order Butterworth filter was applied to the EMG signals at a frequency of 30 Hz, and then demeaned and full wave rectified. Then a fourth-order Butterworth low-pass filter set at 5 Hz was used and eventually normalized by the highest activity [61]. Both participants were required to walk barefoot across the walkway at a normal (1.05–1.1 m/s) speed. In addition, the dynamic trials repeated several times to ensure the repeatability of gait analysis results, and the static trial was also collected.

2.3 Musculoskeletal modeling

The ‘gait 2392’ generic musculoskeletal model in OpenSim software was scaled using static trial data and the participant's body mass [62]. This general model consists of 92 musculo-tendon actuators, and 10 rigid bodies with 23° of freedom (DOF) that was utilized for predicting joint reaction forces (JRFs) and muscle forces. After scaling, the inverse kinematic tool was used to reconstruct desired walking motion. Net moments and muscle forces were calculated using inverse dynamic and static optimization tools, respectively that are already incorporated into the Opensim software. The reactions between two contacting segments of the joints were determined using the Joint Reaction Analysis in OpenSim, which performs as a post-processor step whose input includes GRFs, muscle forces, and the outputs of the inverse kinematic. All of this input were utilised on the free body diagram of the scaled model segments for calculating the joint reactions [39,63,64]. The musculoskeletal model for the participant with hammer toe foot was validated in our previous study [65]. In order to validate the healthy participant model, muscle activation results in OpenSim software were compared against the filtered and normalized similar signals of the EMG test. Comparing the pattern of the muscle activations shows a good agreement with Root-Mean Square Error (RMSE) of 0.21 for tibialis anterior and 0.22 for medial gastrocnemius. Tibialis anterior and medial gastrocnemius muscle activations can be seen in Fig. A1 in Appendix A.

3. Finite element modeling

A 1.5 T MRI scan (Philips Ingenia, spacing between slices: 0.5 mm and slice thickness: 1 mm, sequence 3D mDion Te Hr, TE/TR 9/29) was performed on the left foot in a non-weight-bearing position. Pads and cushions kept the leg and foot at a 90-degree angle. Mimics software (Materialise, Leuven, Belgium) was used to segment and generate a 3D soft and hard tissue model of the participant's left foot with hammer toe based on MRI medical images. The model had 30 bones (medial and lateral sesamoids, 14 phalanges, 5 metatarsals, cuboid, 3 cuneiforms, navicular, calcaneus, talus, and the distal sections of the tibia and fibula) and a bulk soft tissue. 74 cartilage layers for 37 pairs of joints were incorporated to increase the model's accuracy. Surface-to-surface frictionless contact was used to describe the interaction between cartilage layers. To perform the finite element analysis, all components were imported into ABAQUS software (SIMULIA, Providence, USA). Since, the ligaments are not clearly defined in MRI scans, 2174 truss elements were added to the model to identify key ligaments and the plantar fascia which were placed using anatomical atlases [66]. Achilles tendon tied on top of the calcaneus (see Fig. 1). Soft tissue encased all of the other components by embedding the bones, cartilages, ligaments, and Achilles tendon into the bulk of the soft tissue. The ground was represented by a 3D rigid rectangular plate. Based on previous research, contact between the plate and the sole of the foot was regarded surface to surface with a frictional coefficient of 0.6 [67]. The material properties of each components were considered in line with the previous literature as shown in Table 1 [68,69].

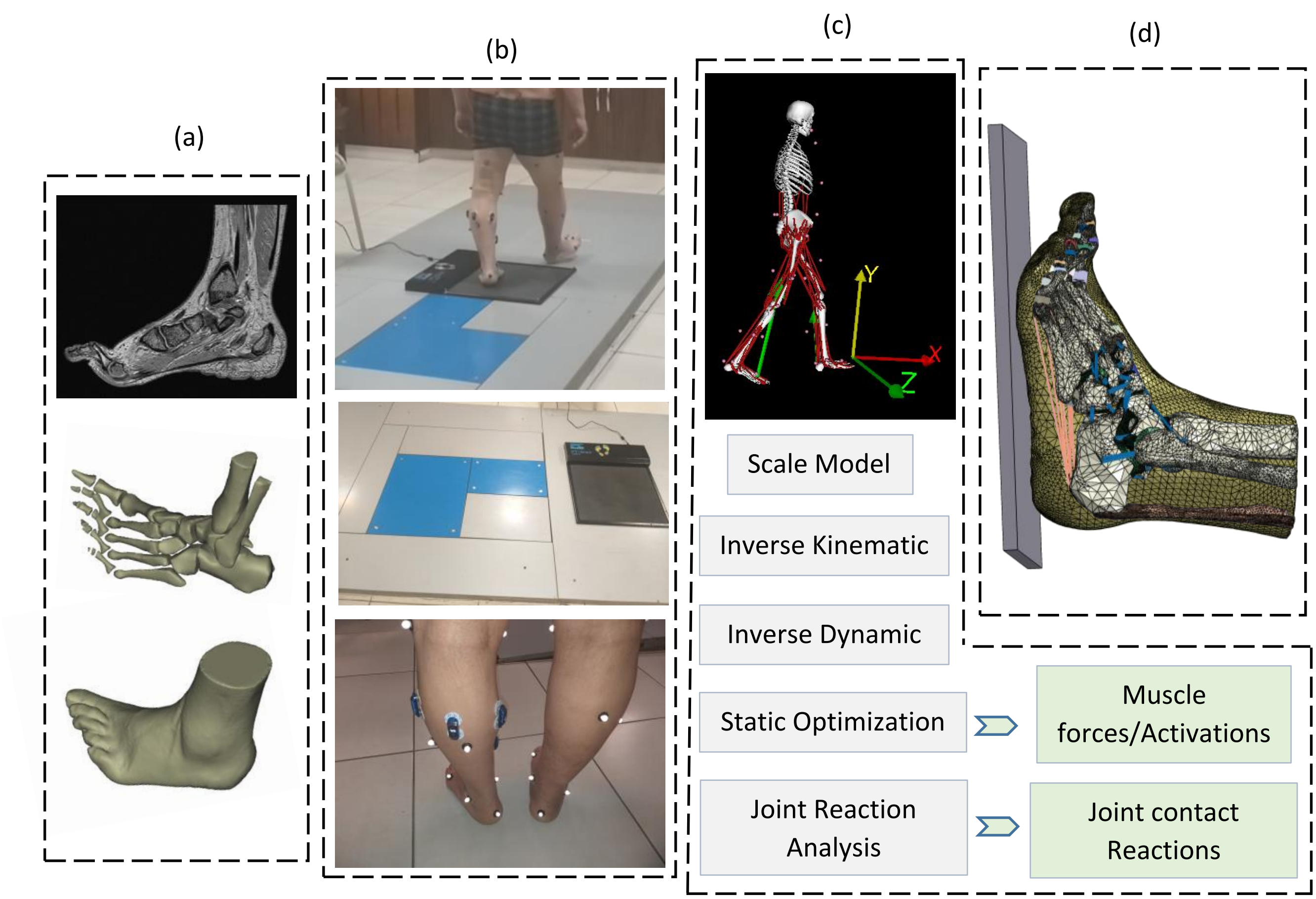

Figure 1. A summary of the steps processed in this study. (a) MRI imaging segmentation in Mimics software for 3D foot model construction (b) Gait analysis (c) Musculoskeletal modeling with Opensim software (d) importing the models into Abaqus software based on foot angles calculated by Vicon software and also inducing the boundary conditions for finite element analysis.

3.1 Walking simulation:

Under quasi-static analysis, five instants (heel strike, early stance, midstance, late stance, and toe-off) of a stance phase throughout the gait cycle were performed. The GRFs and muscle forces were applied to the model at each event. During the analysis, the top surface of the soft tissue, distal tibia, and fibula were fixed as boundary conditions. GRFs were applied to the ground plate at COP. The exact placement of COP on the model was determined according to the relative location of anatomical landmarks and COP. Six muscle forces were applied to the model. The forces of the soleus, medial, and lateral gastrocnemius were applied through the Achilles tendon, and the force of the tibialis anterior, tibialis posterior, and peroneus longus, were located on the relevant bones along the muscle force vectors defined by the OpenSim model [8,70].

4. Result

The comparison of the plantar fascia tension force during walking obtained by finite element (FE) modeling of HTF in the current study, versus the results by Chen et al. [71], and Erdemir et al. [43] are shown in Fig. 2. Muscle forces obtained by Opensim for major active muscle in the propulsion of walking are shown in Fig. 3. As mentioned in section 3, FE modeling was only performed on the left hammer toe foot. Fig. 4 shows the results of lateral/medial displacement of forefoot bones during the four instants of the stance phase that were predicted by finite element modeling. The results of the stress distribution in bony structure and also plantar and internal von Mises stress distribution in sagittal plane view are shown in Fig. 5. It should be noted that the FE model was previously validated by comparing the predicted plantar pressure and the pressure pad results [65]. The results of plantar fascia stresses are shown in Fig. 6. After presenting the results in the sole, the question is whether changes in the location of the COP and the areas involved in weight-bearing due to hammer toe could affect the performance of other parts, such as the joints. For this aim, the results of the foot joint reactions during walking are presented in Fig. 7 and Appendix B for two participants, healthy and hammer toe foot. Forces and moments direction are based on the coordinate shown in Fig. 1.

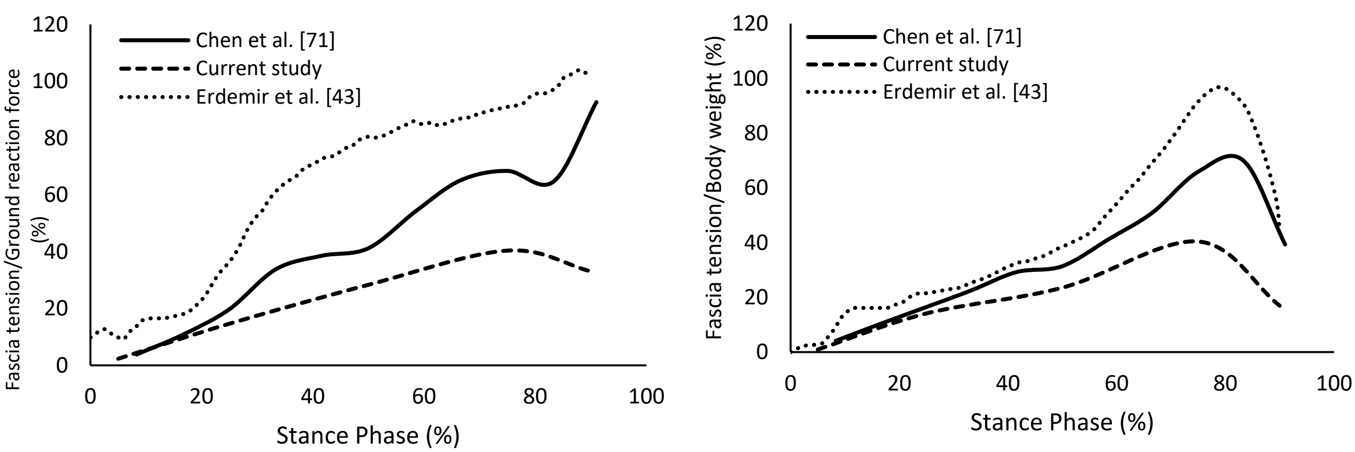

Figure 2. Total tension force induced on plantar fascia normalized by ground reaction force and body weight. The healthy foot study results by Chen et al. [71] and Erdemir et al. [43] were plotted for comparison.

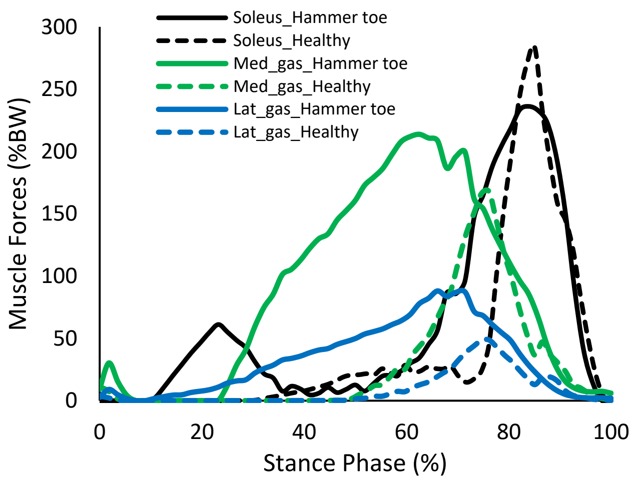

Figure 3. Selective muscle forces during walking for the healthy and hammer toe participants. Soleus, medial and lateral gastrocnemius (Med_gas & Lat_gas) are the major active muscles in propulsion.

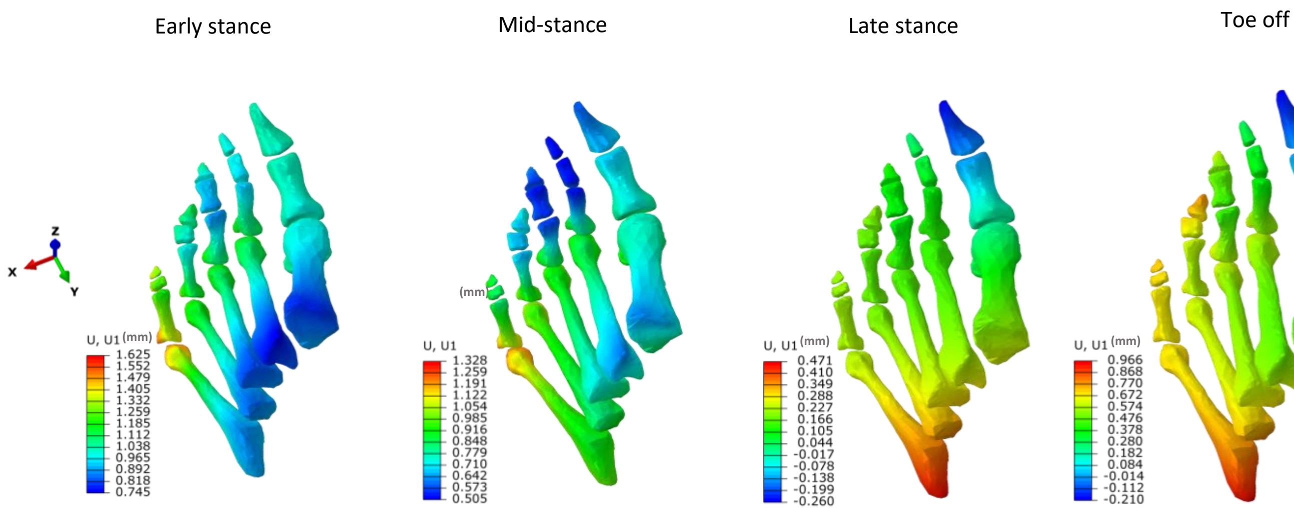

Figure 4. Lateral/medial displacement in hard tissues of hammer toe forefoot at four different events (a) Early stance (b) Mid-stance (c) Late stance (d) Toe off. The result of the heel strike was negligible in comparison to the four other events.

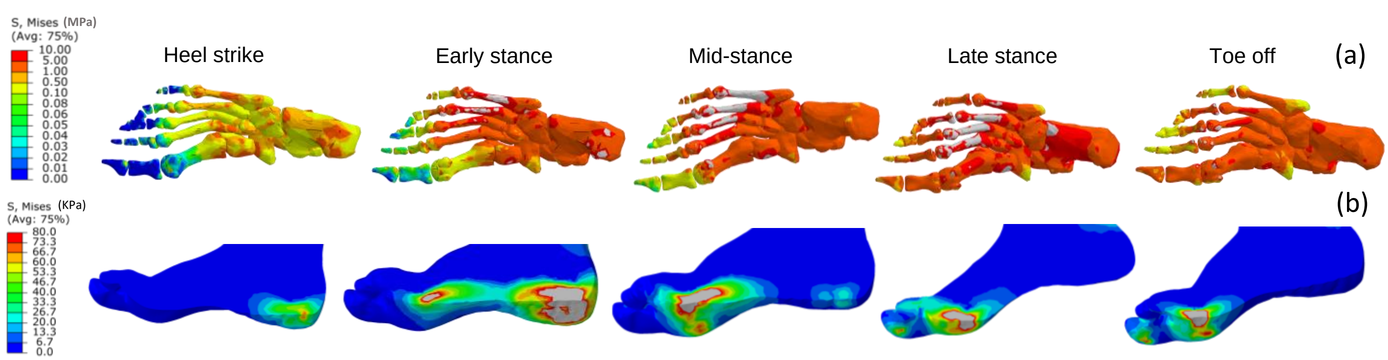

Figure 5. FE simulated internal stress distribution of hammer toe foot at five different instants during stance phase in (a) hard tissues, The light grey colour shows areas with the von Mises higher than 10 (MPa). (b) View cut of soft tissue plantar and internal von Mises stress distribution at HMT foot. Light grey colour shows the von Mises higher than 80 (KPa)

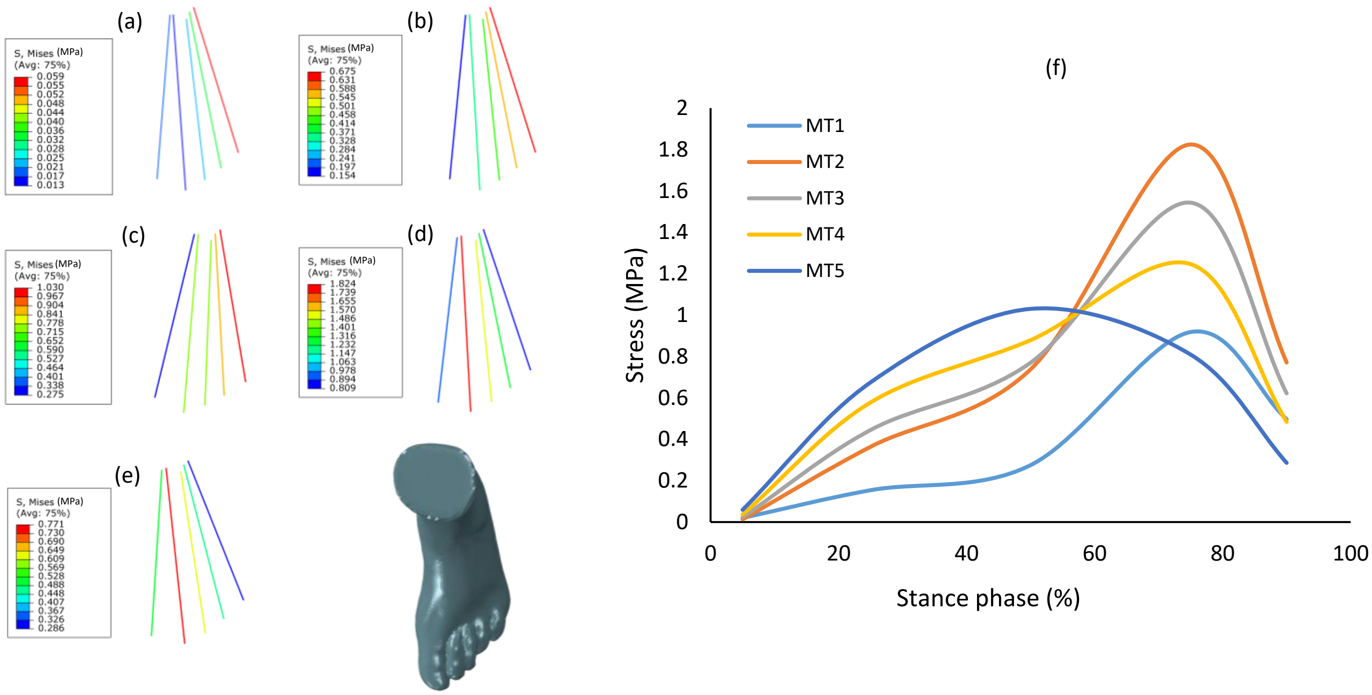

Figure 6. Plantar fascia stresses during walking at five rays of the plantar fascia (under 1st metatarsal (MT1) to 5th metatarsal (MT5)) during five instants of the stance phase in HMT foot. (a) heel strike (b) early stance (c) mid-stance (d) late stance (e) toe off (f) diagram of stress in the plantar fascia rays during the entire stance phase.

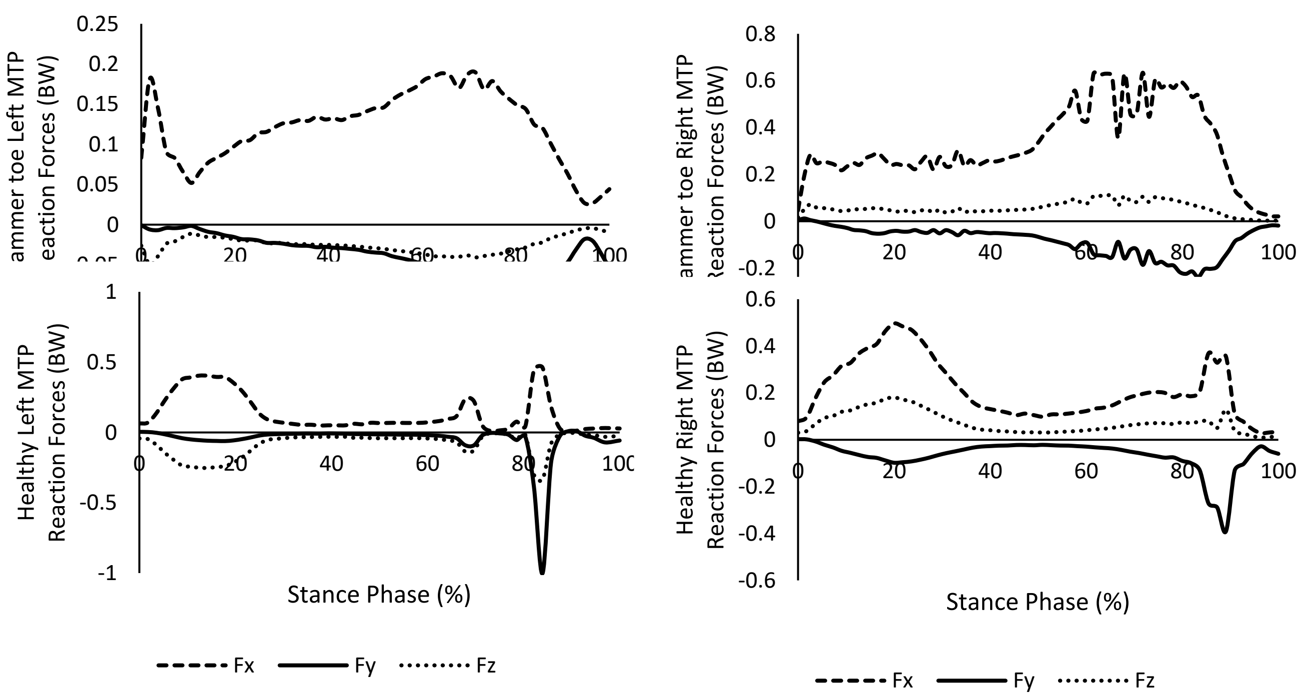

Figure 7. MTP joint reaction forces for hammer toe (left hammer toe and right healthy contralateral foot) and healthy foot participants during the stance phase normalized to the body weight.

Table 1. Material properties of the each part [68, 69] and element type of the components

Components	Young's modulus (MPa)	Poisson's ratio	Cross section (mm²)	Element Type
Hard tissue (bones)	7300	0.3	--	Tetrahedral
Ligament	260	--	18.4	Truss
Cartilage	1	0.4	--	Tetrahedral
Plantar fascia	350	--	290.7	Truss
Ground support	17000	0.1	--	Linear
Achilles tendon	816	3.0	--	Tetrahedral
Encapsulated soft tissue	Hyperelastic (second-order polynomial strain energy potential equation, C_{10} = 0.08556 Nmm^{-2}, C_{01} = -0.05841 Nmm^{-2}, C_{20} = 0.03900 Nmm^{-2}, C_{11} = -0.02319 Nmm^{-2}, C_{02} = 0.00851 Nmm^{-2}, D_1 = 3.65273 mm^2N^{-1}, D_2 = 0.0000 mm^2N^{-1})			Tetrahedral

5. Discussion

The hammer toe is the one of the common deformities of the foot. The investigation of the effect of hammer toe on the other parts of the lower limb can be helpful for better identification of this deformity as well as prevention of progressive damage. For this purpose, the finite element model of the soft and hard tissue, ligament and cartilage in conjunction with the musculoskeletal modeling technique was developed. The validation of the finite element results was performed by comparing the results of the predicted plantar pressure distribution of the foot against the results of the pressure measured experimentally at our previous study. Our estimated peak plantar pressure and also, pressure distribution calculated using FE were in good agreement with the experimental data, with less than 11% error [65]. In order to validate the musculoskeletal model, the results of the predicted intensity of muscle activities were compared with EMG signals.

In line with our previous study [65] and as the soft tissue von Mises stress distribution in Fig. 5 show, the presence of a hammer toe, increase the stress concentration in the forefoot. The hammer toe also increase plantar pressure and internal stresses hence increase the risk of injury and ulcers. In the present study, we showed the other aspects of hammer toe deformity effects on the lower limb.

Wang et al. [72] showed that body weight force (BWF) transmits through the medial metatarsals (1st, 2nd, and 3rd toes and metatarsals), which is in line with the results of peak plantar pressure region in Akrami et al. [8] and also in agreement with the outcome of strain energy in foot parts [73]. In addition, Kalra et al. [74] showed the important role of medial metatarsals, especially the second ray in BWF transmission by investigating 10 cadaveric feet. As shown in Fig. 5, the hammer toe changes the location of the body weight force transmission line to the lateral side of the foot, and the 3rd, 4th, and 5th metatarsals had a significant function in weight-bearing. The function of several parts of the lower limb may be affected as a result of this condition. Previous research on healthy feet found that the fifth metatarsal has lower maximum internal stress compared to other metatarsals [72,75,76]. while fifth metatarsal fractures are thought to occur more frequently than any other metatarsal fractures [77,78], Hence the fact that in our study the hammertoe increased Von Mises stress in the fifth metatarsal, indicates an even further increased risk of fifth metatarsal fracture in this foot deformity. In Fig. 4, the results of lateral/medial displacement of hammer toe foot show that the displacement of the little toe, especially in the metatarsal region, is considerable and indicates expectancy and the probability of bunionette (Tailor's bunion) as the subsequent possible deformity. At the same time, the results of the stress distribution, as well as the displacement of the first toe in the MTP joint, do not demonstrate the possibility of Bunions (Hallux Valgus), as a longer term effect of the hammer toe.

The contact area of the foot with the ground is reduced when the hammer toe occurs, and the toes are less involved in weight-bearing during walking. As shown in Fig. 7, MTP joint reaction force in the foot with hammer toe is less than the healthy foot. Also the stress distribution results in Fig. 5 indicate the significant difference between metatarsals and toes stresses, and this issue shows a shift in the contribution of the toes in weight-bearing to the metatarsals. Furthermore, this means a reduction in foot length which acts like a flat spring. The stiffness of the flat spring rises as its length decreases, so the hammer toe exhibit a more rigid foot, and this condition has an impact on the forces in the lower limb. A rigid foot is less likely to be able to absorb shocks, resulting in intense ground forces being imposed on the foot [79,80]. A more rigid foot causes higher ankle, knee, and hip joint reaction forces, which in this study appeared in knee forces with 50% higher than a healthy foot and where the double hump in the vertical knee and hip reaction forces disappeared and a monotonically increasing trend was observed, as shown in figures B1 and B2 at Appendix B.

The results of the joint reactions indicate the distinction of the knee abduction moment pattern, as well as the amount of force on the knee and hip between hammer toe and healthy foot as shown in Appendix B. Our results of the healthy foot (pattern and magnitude) are in line with previous studies [81,82]. A notable point on the peak of the reaction moments is that since the hammer toe shifted the position of the COP to laterally, the moment arm of the GRF has been reduced on joints, which is in line with the previous finding [83]. For this reason, the peak reaction moments in the hammer toe foot are lower than the values in the healthy foot. The plantar fascia is a significant contributing factor to foot stability [51,84]. As shown in Fig. 6, the plantar fascia capacity is compromised in the hammer toe foot, and as a result, there is less shock and energy absorption expected to occur in the plantar fascia of the hammer toe foot. Caravaggi et al. [85] showed that the overall tensile plantar fascia load decreases from medial to lateral in healthy foot and also the previous studies showed that the medial side of the plantar fascia has higher stress during walking [86], and the medial side was reported as showing areas with maximum stress [46,71] which show that the first ray has a significant role in elastic energy storage. On the other hand, plantar fasciitis occurs as a consequence of excess mechanical load on the fascia [87,88]. Results of this study show that for the hammer toe as the deformity and consequent poor windlass mechanism, the maximum tensile load does not occur at the medial side of the plantar fascia, and the first ray of the plantar fascia under the 1st MTP has lower tensile force during walking shown in Fig. 6. Furthermore, the result of PF stresses shows that in addition to the 2nd ray, the lateral side of the PF is expected to be more prone to the onset of small tears and injury in HTF as a result of the continuous forces induced during the stance phase of gait. The need for more muscular forces will be reduced by storing energy in tendons and ligaments during walking [44,89,90] that is expected to be up to 17% of the overall mechanical energy spent during walking [91]. As shown in Fig. 3, due to the reduction of the elastic stored energy at the PF, the required power and muscle forces for HTF are higher than HF, and this issue raises the metabolic cost. The soleus,medial and lateral gastrocnemius make a contribution of 93% of the plantar flexion torque during a step [92]. The tensions in the Achilles tendon and plantar fascia are mechanically connected. Increasing the PF tension, in addition to providing integrity to the bony arch structure, increases the tension in the Achilles tendon, which is likely to reduce the metabolic cost of walking [93]. However this does not happen in HTF. As shown in Fig. 2, PF force significantly reduced in HTF, and as shown in Fig. 3, this issue demands extra soleus, medial and lateral gastrocnemius muscle force for effective propulsion and this matter makes the body use more energy during walking.

According to Zhang et al. [94], injuries in joints, such as the knee joint and osteoarthritis, will increase the force induced on the foot. Similarly, based on the results of soft tissue stress distribution shown in Fig. 5, deformity at the metatarsal head makes the stress concentration and increases internal and plantar stresses in hammer toe foot which is consistent with previous studies [23,65].

6. Conclusion

This study found that the hammer toe deformity changes the pattern and line of bodyweight force transmission and also affects the forces and moments of the joints. Also, this study revealed that hammer toe deformity makes dorsiflexion of the toes and the windlass mechanism less effective during walking. Specifically, the FE results showed that plantar fascia (PF) in HTF played a less dominant role in bearing load in comparison to HF. Also, the results indicated that the stored elastic energy in PF was less in HTF compared to the HF, which can indicate an increased metabolic cost during walking. Higher stresses in the plantar fascia in HTF show not only the medial part but also the lateral part may be exposed to plantar fasciitis. Internal stress distribution shows that the majority of bodyweight force is transmitted through the lateral metatarsals in hammer toe foot, and the probability of a fifth metatarsal fracture and also progressive deformity like Tailor's bunion was subsequently increased. The MSM results show the joint reaction forces and moments in the hammer toe foot have deviated from the normal function, where the values of the metatarsophalangeal joint reactions in the hammer toe are less than the healthy foot. Also, HTF joint forces have a more extended period of monotonic increase during the stance phase in comparison to HF. In this way, a cycle can form between foot deformity, with changes in body weight force transmission line, and deviation of joint reactions and plantar fascia function from normal leading to increased plantar pressure, and increased internal stress concentration, which in turn lead to further foot deformities. One of the advantages of the FE analysis is the capability to conduct a parametric investigation. This allows the ability to generate results without the need for difficult and costly in vivo experiments on a number of participants [95].

In conclusion, it can be stated that a cycle between deformity, changes in BWF transmission line, joint and PF malfunction, increased plantar pressures, increase in areas of high internal stress concentration, and increased internal stresses occur in hammer toe foot that can lead to an increase in the risk of ulceration for the diabetic foot (figure C1).

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Appendix A

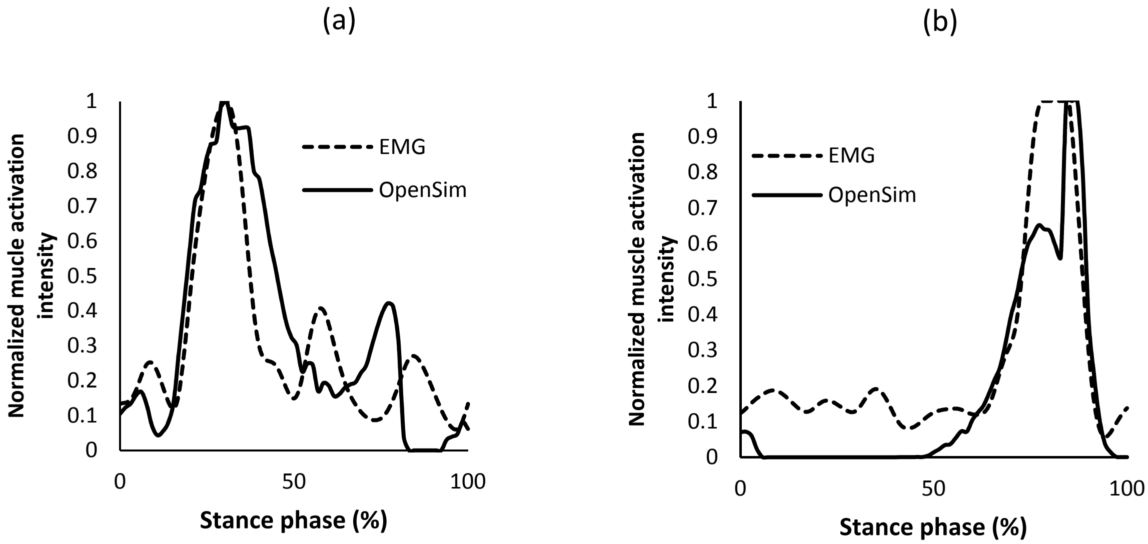

Figure A1. Comparing the intensity of muscle activation between EMG data and OpenSim results (a) Tibialis anterior (B) Medial gastrocnemius.

Appendix B

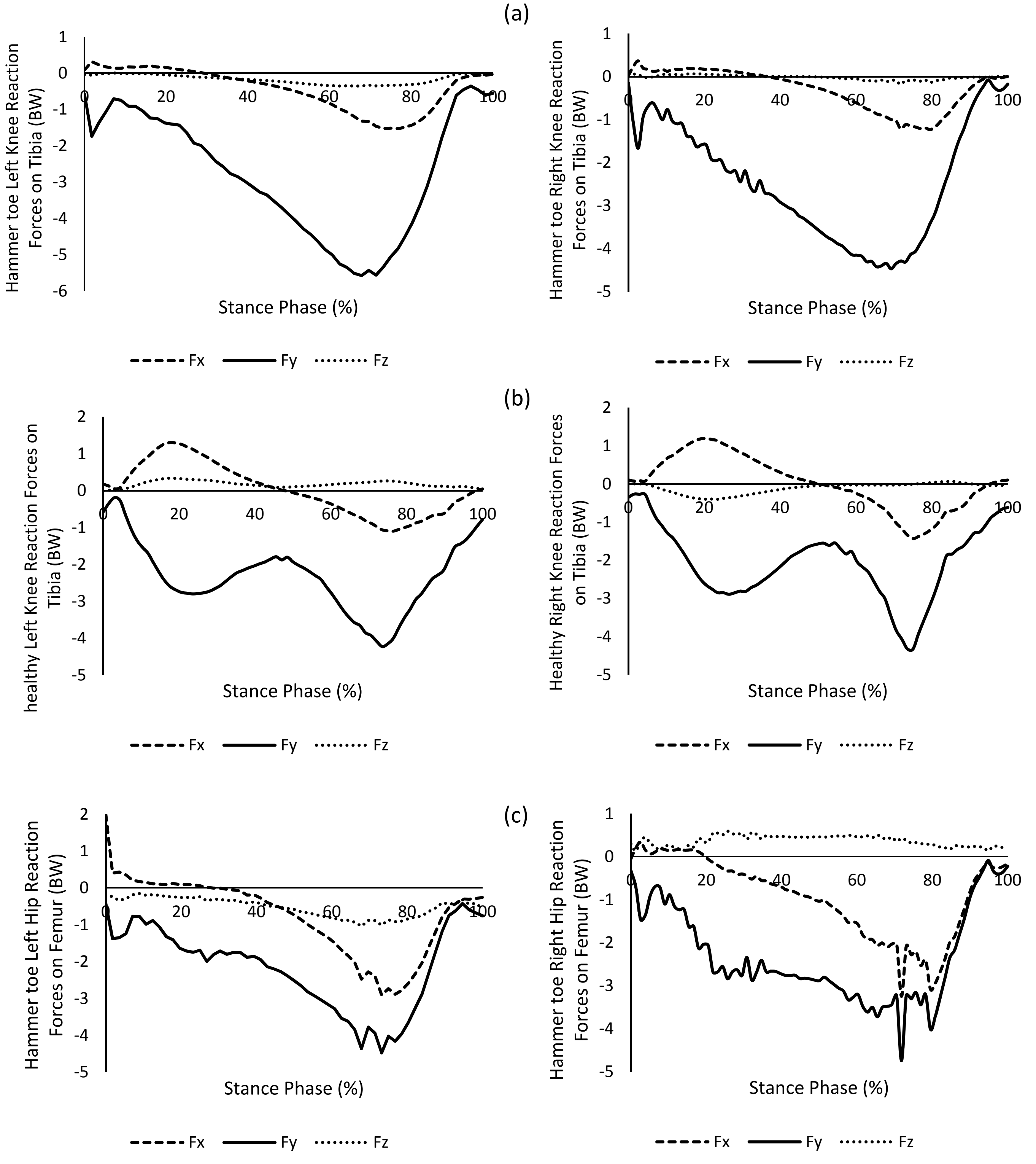

Figure B1. Joint Reactions for hammer toe (left hammer toe and healthy contralateral right foot) and healthy foot participants during the stance phase. (a) Hammer toe knee forces (b) Healthy knee forces (c) Hammer toe hip forces

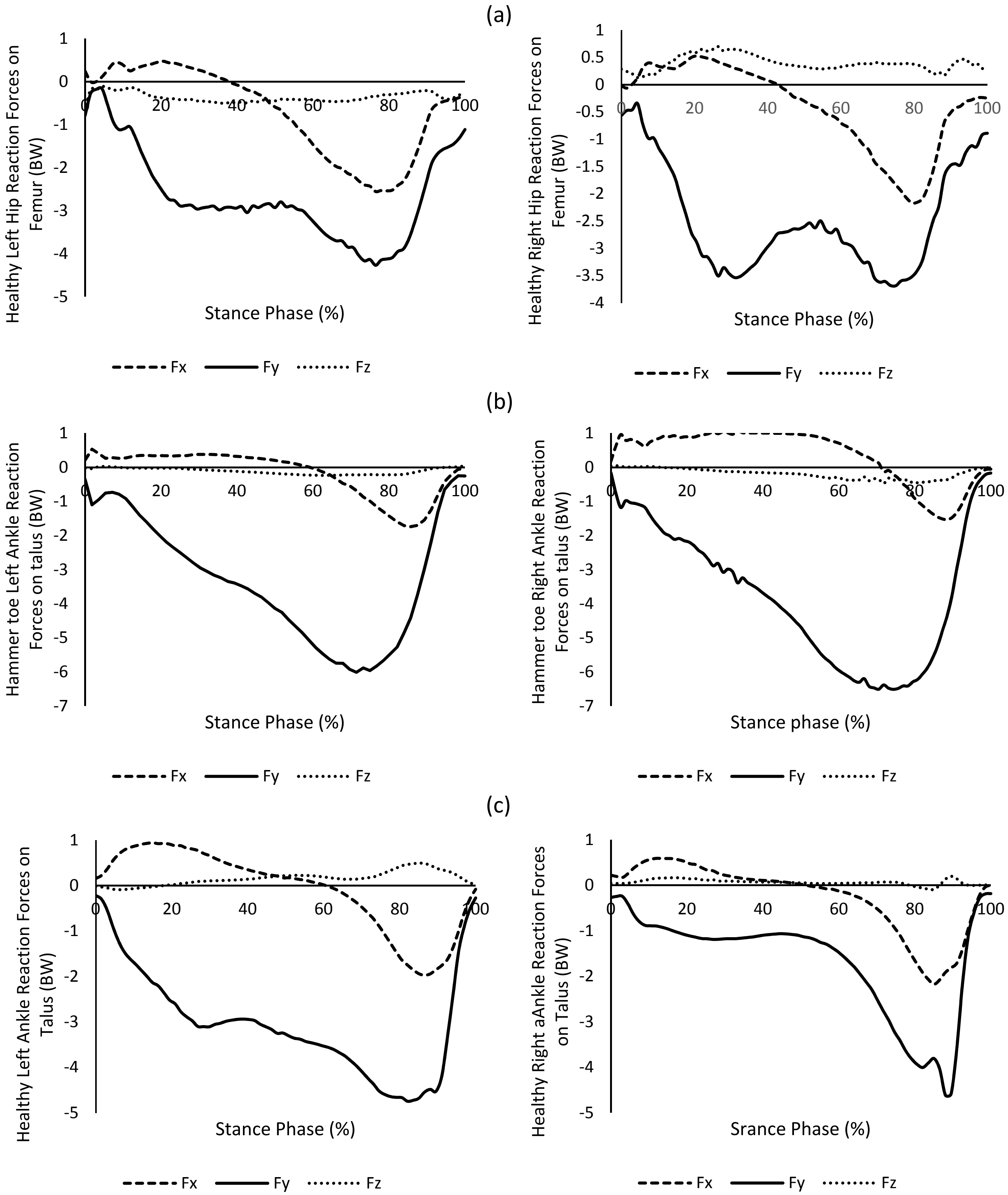

Figure B2. Joint Reactions for hammer toe (left hammer toe and healthy contralateral right foot) and healthy foot participants during the stance phase. (a) Healthy hip force (b) Hammer toe ankle force (c) Healthy ankle forces

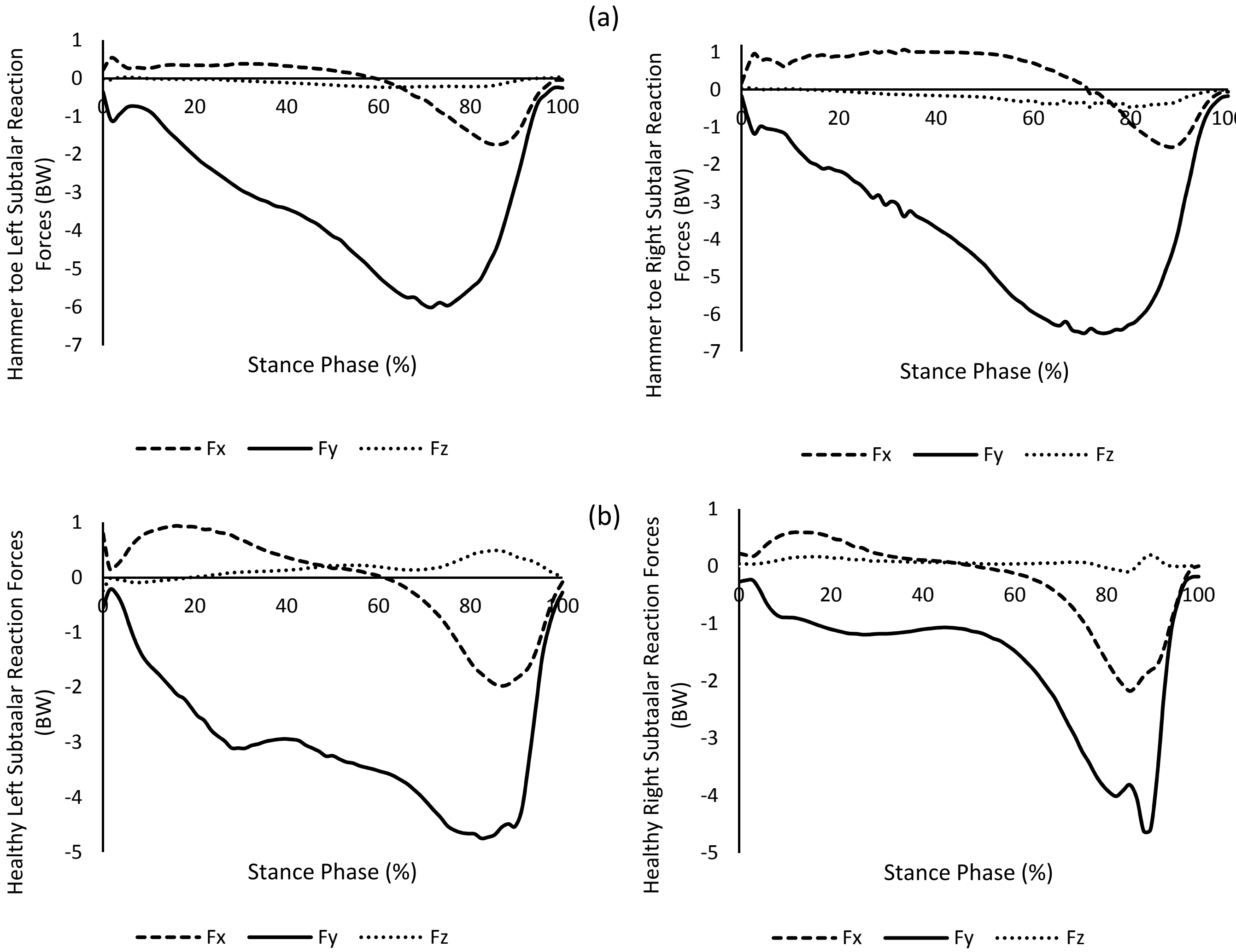

Figure B3. Joint Reactions for hammer toe (left hammer toe and healthy contralateral right foot) and healthy foot participants during the stance phase. (a) Hammer toe subtalar forces (b) Healthy subtalar force

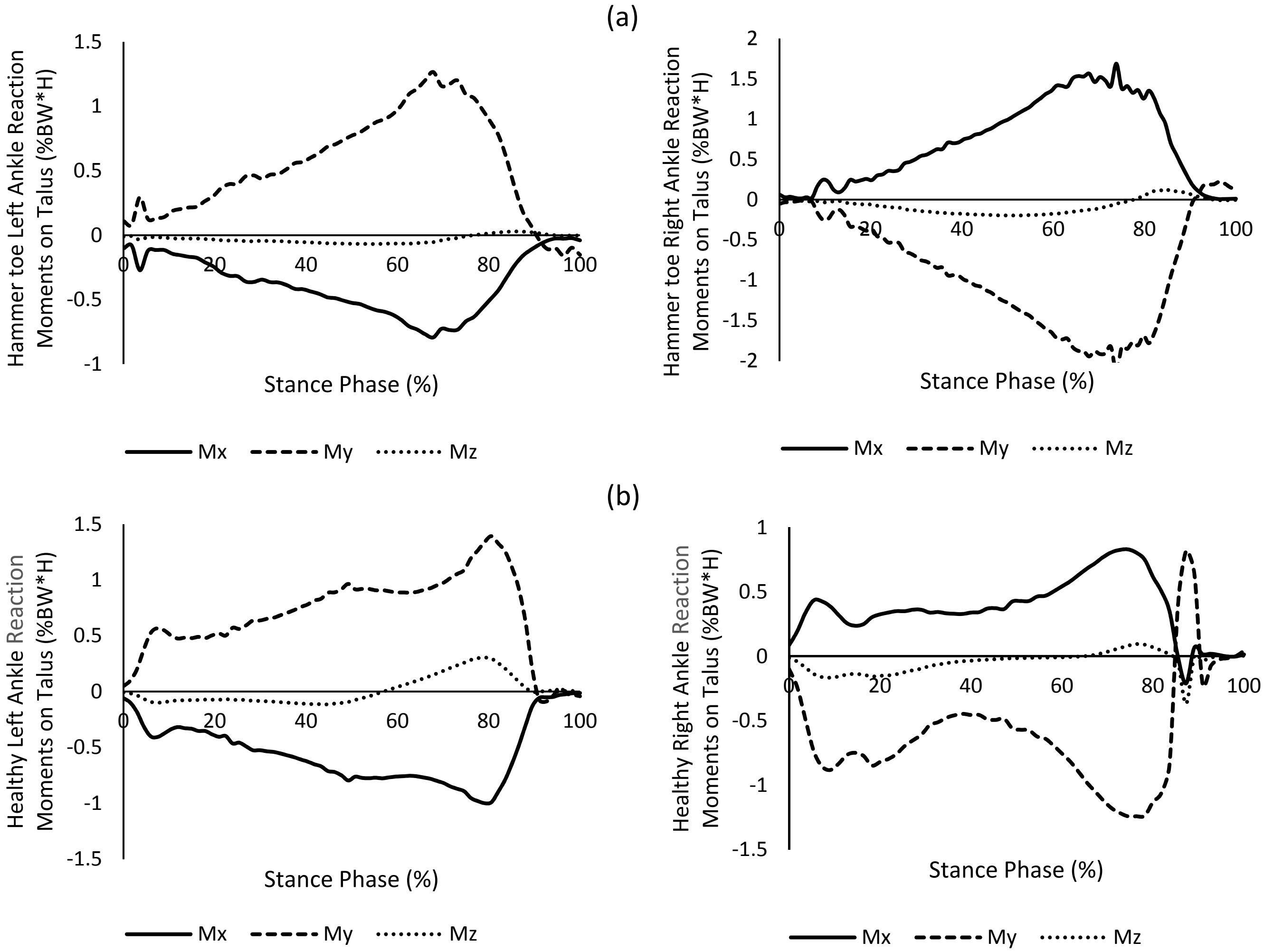

Figure B4. Joint Reactions for hammer toe (left hammer toe and healthy contralateral right foot) and healthy foot participants during the stance phase. (a) Hammer toe ankle moments (b) Healthy ankle moments

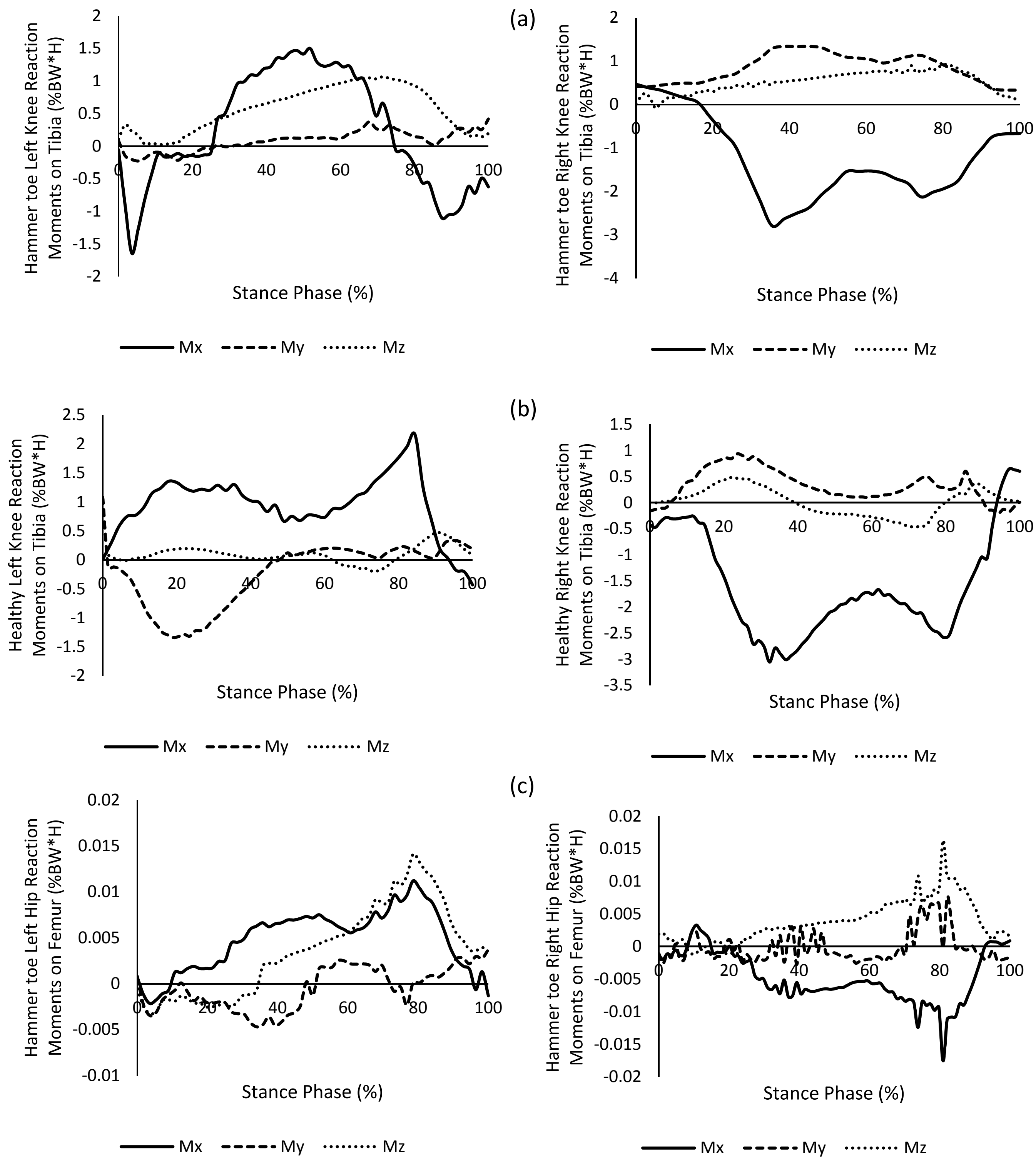

Figure B5. Joint Reactions for hammer toe (left hammer toe and healthy contralateral right foot) and healthy foot participants during the stance phase. (a) Hammer toe knee moments (b) Healthy knee moments (c) Hammer toe hip moments

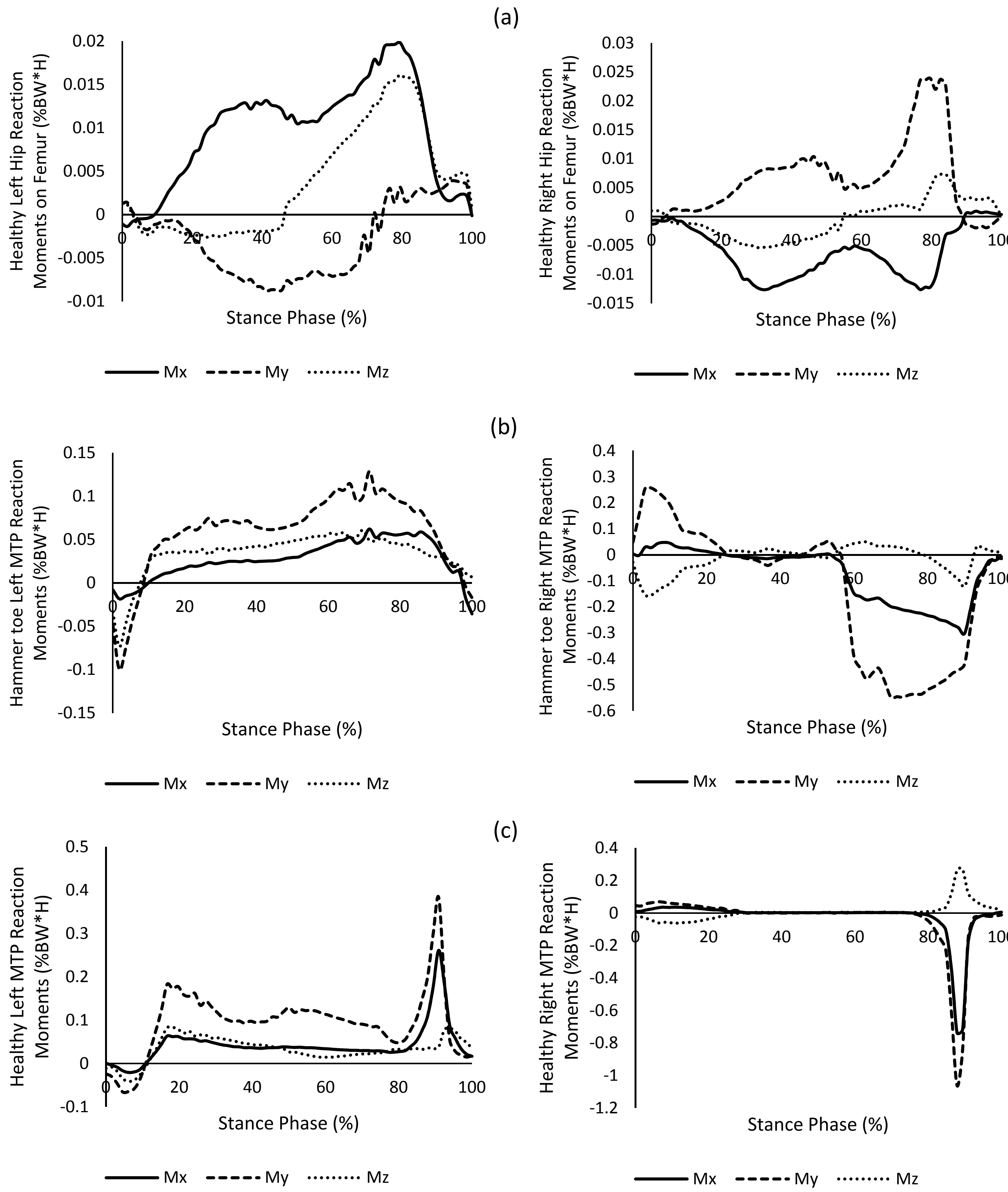

Figure B6 . Joint Reactions for hammer toe (left hammer toe and healthy contralateral right foot) and healthy foot participants during the stance phase. (a) Healthy hip moments (b) Hammer toe MTP moments (c) Healthy MTP moments

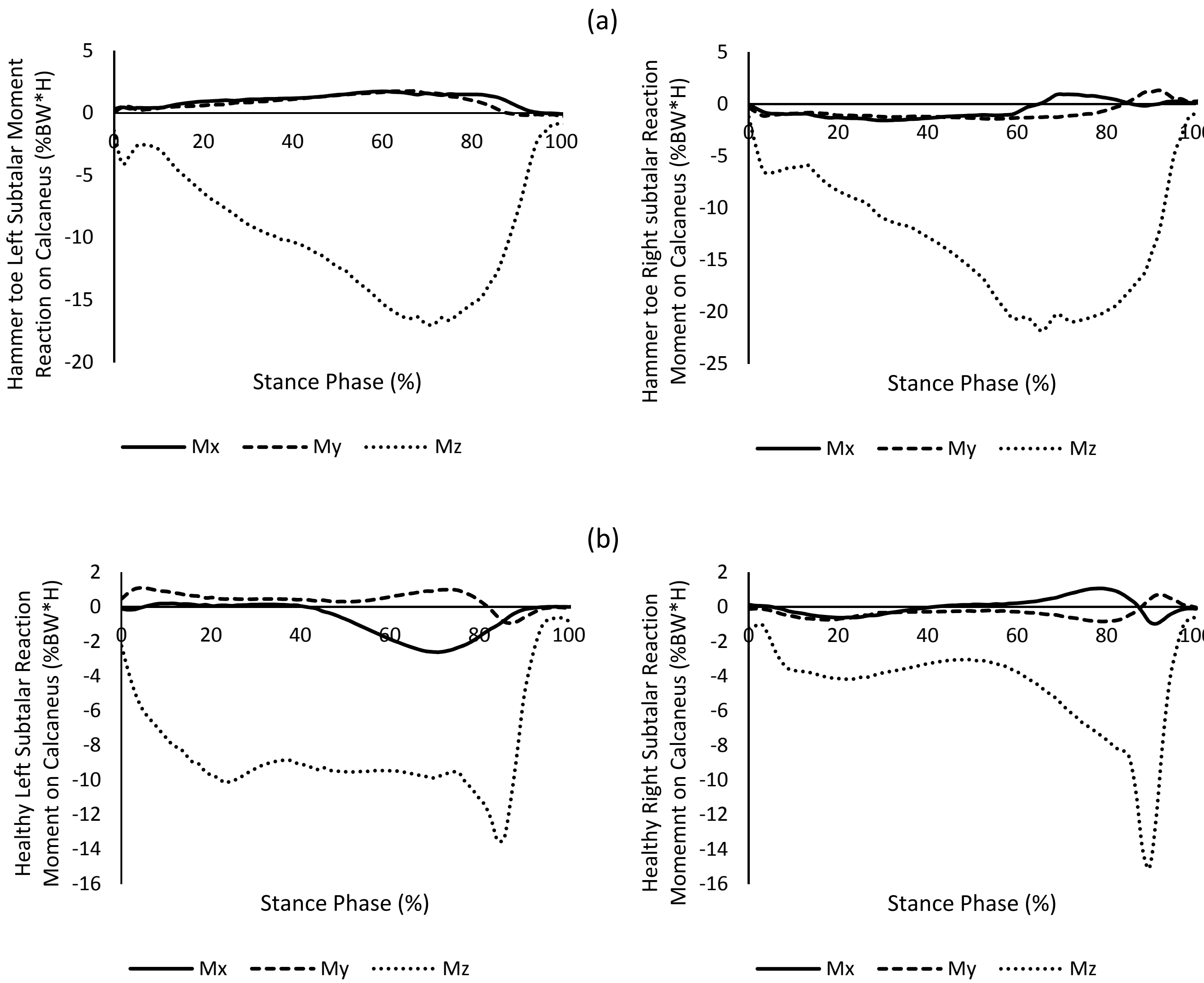

Figure B7 . Joint Reactions for hammer toe (left hammer toe and healthy contralateral right foot) and healthy foot participants during the stance phase. (a) Hammer toe subtalar moments (b) Healthy subtalar moments

Appendix C

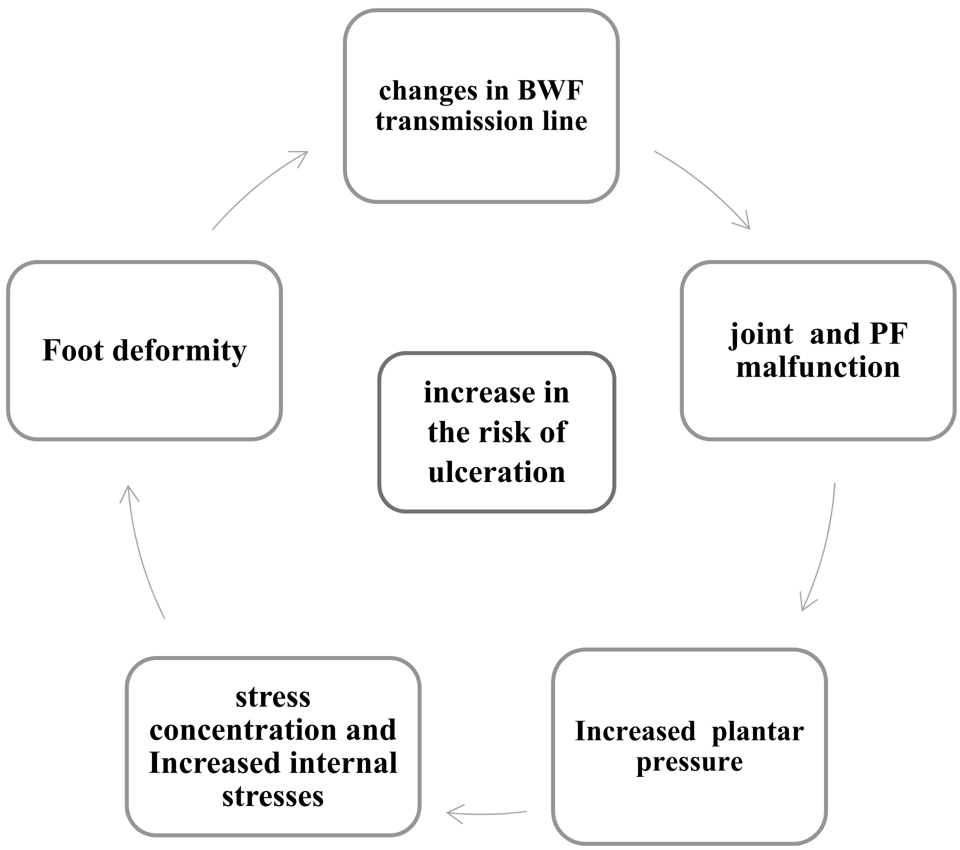

Figure C1. The cycle of factors contributes to an increased risk of ulceration in the hammer toe foot.