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Effects of corrective insole on leg muscle activation and lower extremity alignment for farmers with pronated foot

Abstract

Background: Previous research indicates the nature of certain work environments may cause healthy workers to experience significant performance deterioration comparable to physical disability. Execution of strenuous activities in conjunction with slippery and viscous muddy working terrain in rice cultivation leads to a high prevalence of farmer musculoskeletal disorders and malalignments. Recommended intervention strategies originally designed for congenitally disabled individuals may also be applicable to farmers, including a simple corrective wedge to reduce foot eversion. The objective of the present study was to investigate the effects of corrective wedges on lower extremity muscle activity and alignment when subjects stood on flat rigid ground or muddy terrain, simulating typical work conditions encountered by Thai rice farmers.

Methods: Nine healthy farmers with pronated feet were recruited to participate in the study and wedges were custom fabricated for each participant based on physical therapy assessment and by using rapid prototyping techniques. Participants were asked to stand barefoot or with wedges on the two surface types.

Results: Results showed that foot pronation and knee valgus improved (average of 5.5 – 16.1 degrees) when participants were equipped with corrective wedges. The muscle activity of the peroneus longus and the tibialis anterior increased for muddy terrain, as compared with the rigid surface. In general, the wedges induced less tibialis anterior activity and greater peroneus longus activity compared to when participants were standing barefoot. An elevation in evertor muscle activity may reflect stretching of the shortened muscle as a result of the reduced degree of foot pronation.

Conclusions: The findings demonstrate the positive effects of corrective insole usage for farmers with pronated feet, including improved lower extremity alignment and invertor muscle activity reduction for both rigid and muddy terrains.

Keywords: Medial wedge insole; muscle activity; foot pronation; lower extremity alignment; working surface condition

1. Introduction

The nature of certain work requirements and environments has been identified as cause of healthy workers performance degradation comparable to physical disabilities [1, 2]. For example, foot pronation, which can be defined as the motion of the foot articulations that allow the foot to become more prone to the supporting surface, thereby increasing the ground contact surface area of the foot [3]. Excessive foot pronation can result from a loss of muscle control due to neurological dysfunction [4, 5]. Such muscle injury conditions may also occur in rice farmers due to compensation for foot instability and control of body alignment while walking on slippery and highly viscous mud in rice paddy fields [6, 7]. The extreme environment and strenuous work requirements of certain rice cultivation processes causes farmers to develop a high prevalence of musculoskeletal disorders (MSDs) and malalignments in various body parts [8; 9]. The prevalence of MSDs among rice farmers in Thailand has been found to be between 10.3-73.3% [10]. In a recent study which investigated indications and triggers of musculoskeletal and lower limb disability conditions [11], foot pronation was identified as the predominant disorder among rice farmers in Khon Kaen, Thailand, with a percentage of 36.1%. An analysis of the risk factors showed that years of farming experience correlated strongly with the specific type of foot malalignment.

Rice farming activities in Thailand mostly involve manual labor (National Statistical Office), which includes frequent lifting of heavy loads and requires awkward postures and prolonged standing [12]. In addition, the preference of farmers to perform their work with bare feet is suspected to aggravate MSDs and lower limb malalignments, as viscous muddy paddy fields increase force loading on joints and muscles of the lower extremities [13]. In addition, abnormal foot structures can further raise the risk of lower limb injuries [14, 15], while abnormalities in foot pronation might result in passive hypermobility and instability of specific joints in the foot [16]. Consequently, individuals suffering from pronated feet may feel unstable during weight bearing, demonstrate poorer balance, and demonstrate a higher risk of injury due to slipping or falling [17]. In addition, there is evidence of a close relationship between variations in foot structure among healthy individuals and the risk of lower limb injury, possibly due to changes in lower limb muscle activity [18]. This research indicated individuals with pronated feet depend on additional muscular support while walking or running [18] and induced fatigue can increase the risk of injury [19].

However, despite knowledge and general awareness of the above hazards, successful intervention designs for rice farmers are limited [20, 21].

Studies of intervention strategies for individuals with disabilities have suggested methods could also be applied to support healthy individuals working in extreme environments or aid in prevention of occupation-related injury [2]. Along these lines, our previous work revealed similarities in pain perception, malalignment, and origin of structural impairment between patients with a neurological disorder, specifically cerebral palsy (CP) with spastic diplegia, and rice farmers [7]. Patients diagnosed with CP showed extensive knee valgus and foot pronation, matching well with clinical symptoms observed among rice farmers. A subsequent study reviewed and recommended several ergonomic interventions, originally designed for CP patients, to be applicable to rice farmers [22]. The study revealed most existing and proposed interventions for farmers are based on educational programs and tool redesigns. There has also been no attempt to adapt readily available interventions for congenitally disabled populations, including patients with CP, for the healthy farmer workforce. Based on previous study [22], it concluded that orthotic devices could have great value for treatment of foot pronation, which is in-line with other clinical and rehabilitation medicine studies proposing applications of molded foot orthoses [23], removable external orthotic devices [24, 25], and inserts or specially designed insoles [26, 27]. However, molded orthotics are expensive and require many manufacturing steps in production of specific structural elements. Moreover, molded orthotics are difficult to fit into existing footwear due to bulkiness of the material [28]. Removable external orthotic devices (e.g., ankle foot orthoses) may restrict movement due to rigid designs; whereas, orthotics with adaptive control systems are expensive and require an external power source [24, 25]. A simple wedge has been proposed as an alternative treatment device and is often selected by medical practitioners to provide patients with direct therapy. Such corrective wedges can be used in footwear where space is restricted and require significantly less manufacturing time (up to 3 times less) and cost up to 2.5 times less, as compared with molded orthotics [27]. Recent advances in custom orthotic production make use of 3D-scanning technology to acquire an appropriate model of the patient's feet, as well as rapid prototyping to accelerate the production process [29, 30]. This procedure allows custom orthotics to be quickly designed and manufactured and, therefore, represents a highly practical means of development of interventions for rice farmers.

The objective of the present study was to investigate the effects of simple corrective wedges on farmer leg muscle activity and foot and knee alignments, induced by standing on different work terrain surfaces, including normal flat rigid ground and a muddy surface. The types of terrain were selected based on conditions typically encountered by workers during performance of rice cultivation tasks. It was hypothesized that wedge insoles would help to correct deviations of foot and knee alignments. Muddy terrain was expected to induce greater muscle activity related to foot inversion and eversion (i.e., tibialis anterior (TA) and peroneus longus (PL), respectively). A proposed medial wedge insole was expected to help reduce muscle activity for both terrain conditions and demonstrate applicability of orthotic devices, primarily used by the disabled population, to extend to the agricultural workforce.

2. Materials and methods

2.1. Participants

Experienced rice farmers (males and females aged between 20-59 years) were recruited from Khon Kaen Province, Thailand. Participants were required to have at least 1 year of experience in rice cultivation and to have no prior medical history affecting lower extremity alignment, such as surgery and/or a fracture. Subsequently, rear foot and medial longitudinal arch angles of all participants were measured, based on Jonson and Gross's method [31]. The participants were included in the study upon diagnosis of foot pronation (i.e. a rear foot angle greater than 9 degrees and a medial longitudinal arch angle less than 134 degrees). The subject sample allowed for investigation of changes in lower extremity alignment and muscle activity. The experiment was conducted with a sample size of 9 subjects, based on previous studies in which the sample size ranged from 9-70 subjects [26, 27]. All participants gave a written informed consent. Study of these participants was approved by the Khon Kaen University Ethics Committee for Human Research.

2.2. Corrective insole design and fabrication

Corrective insoles were custom designed and manufactured for each participant. The size of the insoles was determined by the participants' shoe size, which was either 10", 10.5", or 11" in the current study (Fig. 1). The fabrication process of corrective insole started from the reverse engineering of the foot anatomy and according to the three steps, including (1) 3D anatomy acqusition, (2) 3D CAD modeling of the corrective insole, and (3) 3D printing process of the corrective insole. On the data acquisition step, a scanning process was conducted using a 3D scanner and a clinical examination conducted by physical therapists. A Sense 3D scanner (3D Systems, Inc., Rock Hill, USA) was used for acquisition of a 3D image of each participant's feet while the subject was seated with legs held out horizontally, supported on a stable chair of the same height. On the 3D CAD modeling step, the 3D image of the foot was used to create a 3D computer-based model of the insole and the custom filling of the arch using the SolidWorks software package (Dassault Systèmes SolidWorks Corporation, Waltham, USA). Based on clinical examination and measurement of foot malalignment (described in measurement of lower extremity alignment section), the specific height and angle of the medial forefoot wedge, medial rear foot wedge and heel lift (required to correct the individual foot alignment) were identified and incorporated in the model. Specifically, a 1/8-inch (0.318 cm) heel lift was prescribed if participants exhibited less than neutral dorsiflexion at the ankle. A medial forefoot wedge, with the angular magnitude of measured forefoot varus, was included if the participant exhibited forefoot varus more than or equal to 5 degrees. If the rearfoot angle of the participant was more than 9 degrees, a medial rearfoot wedge was included, with the angular magnitude that corrected the rearfoot angle to be less than 9 degrees but not exceed a 1/8-inch (0.318 cm) height of wedge. Once the design was completed, the wedge insole was manufactured by printing polylactic acid (PLA) filaments on a FlashForge 3D Printer Creator Pro (Zhejiang Flashforge3D technology Co.,LTD, Jinhua, China).


(A) (B) (C)

Fig. 1. Examples of medial wedge insole design of sizes: (A) 10” (B) 10.5”; and (C) 11”.

2.3. Measurement of lower extremity alignment

As foot pronation and knee valgus are linked deformities, the alignments of rear foot angle, medial longitudinal arch angle, quadriceps (Q) angle, and tibiofemoral angle were measured in this study. The measurements were conducted in a standardized standing position and were based on the methods described in ([11], Fig. 2). All measurements were repeated 3 times by a single physical therapist. Participants’ feet were classified as showing normal alignment when the rear foot angle ranged between 3 - 9 degrees and the medial longitudinal arch angle ranged between 134 - 150 degrees [31]. A genu valgus (knock-knee) was identified when the Q-angle was greater than 18 degrees or the tibiofemoral angle was less than 173 degrees. For normal knee alignment, the Q-angle of males and females is approximately 10–13 degrees and 15–18 degrees, respectively, and the tibiofemoral angle is approximately 173 -180 degrees [32, 33].

Fig. 2. Lower extremity alignment measurement methods for: (A) rear foot angle; (B) quadriceps angle; (C) tibiofemoral angle and; (D) medial longitudinal arch angle.

2.4. Measurement of lower extremity muscle activity

The foot invertor and evertor muscles, TA and PL, respectively, were connected to a wireless electromyograph (EMG; Wave Plus, Cometa, Milan, Italy), after which the EMG Easy Report software (MerloBioEngineering, Parma, Italy) was used to measure and analyze muscle activity. To reduce impedance, the skin underlying the electrodes was shaved, scraped with sand paper, and cleaned with alcohol. Two pairs of surface EMG electrodes were placed 2 cm apart over anatomical locations of TA and PL muscles, based on the guidelines from previous research [34]. Specifically, the electrodes were placed 3 cm below the fibular head to measure PL muscle activity, and 1 cm lateral to the tibia edge and 8 cm below the tibial tuberosity to measure TA muscle activity (Fig. 3). Muscle activity of the TA and the PL was collected simultaneously from the participants' right leg at a sampling rate of 2000 Hz. EMG data were filtered using 20 – 500 Hz bandpass and 50 Hz notch filters. The root mean square (RMS) values were obtained and normalized as a percentage of the maximal voluntary isometric contraction (%MVIC). The MVIC value of the PL and TA were measured in the neutral ankle joint position, based on guidelines from a previous study [35].

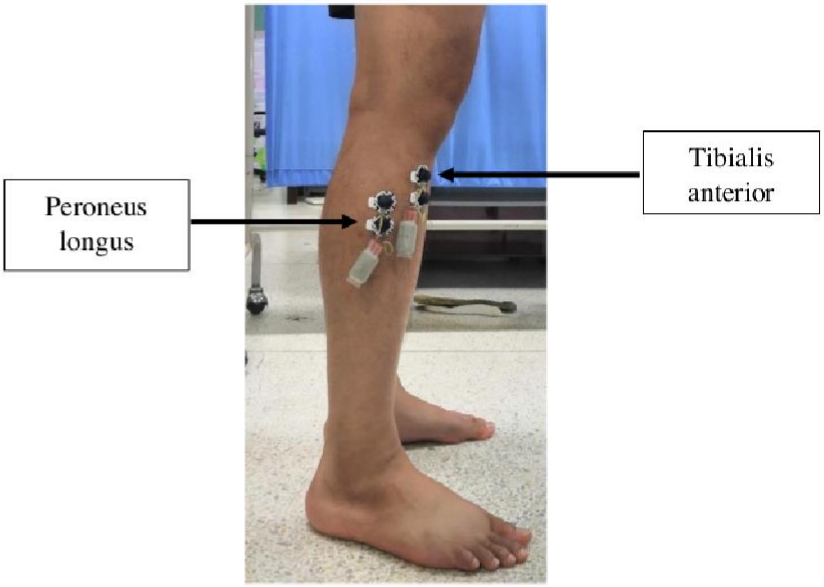
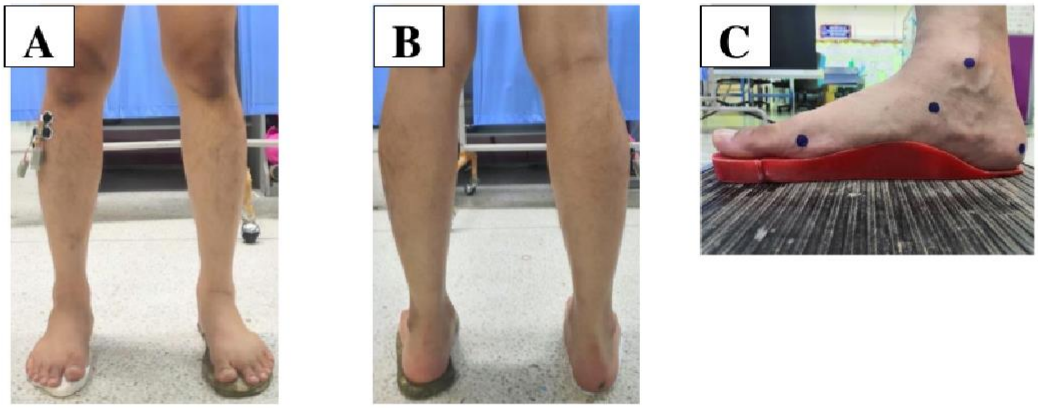


Fig. 3. Illustration of EMG electrode placements of peroneus longus (PL) and tibialis anterior (TA).

2.5. Experimental procedure

The study consisted of two footwear conditions, (1) barefoot (BF) and (2) with corrective insole (CI); and two work terrain surfaces, (1) flat rigid and (2) muddy surface. For the latter condition, we used a mud-filled container with a flat bottom surface. The order of participant exposure to the experimental conditions was randomized. Before starting the experiment, participants were given a 5-minute rest. Subsequently, they were instructed to assume a standing position with a stance width of shoulder-width apart, maintain a stable posture, and look straight ahead for 1 minute while lower extremity alignments were measured and EMG data were recorded. Due to limited visibility, the foot alignments, including rear foot angle and medial longitudinal arch angle, could not be measured when participants were standing in the mud. Fig. 4 illustrates a participant equipped with corrective insoles standing on the two work terrain conditions. All participants were provided a 5-minute break between each experiment condition to relieve any potential muscle fatigue, based on a recommendation from prior research [36]. To prevent potential injury through falling or slipping, the corrective insoles were secured by plastic wraps to the participants' feet while standing on muddy terrain.



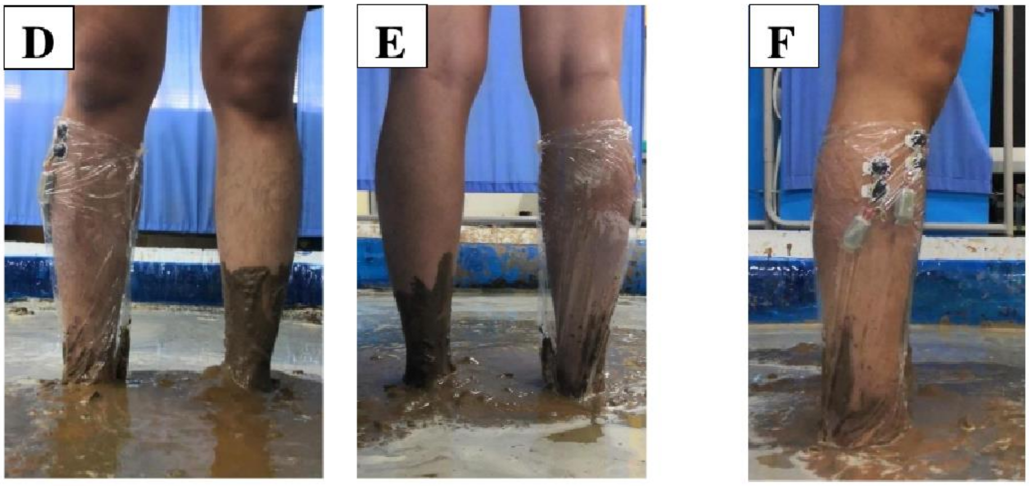


Fig. 4. Illustration of standing posture with corrective insoles: (A-C) front, back and medial view (to demonstrate a thickness of wedge) on flat rigid terrain and; (D-F) front, back and lateral view (due to a difficulty to obtain the medial side of foot) on muddy terrain.

3. Results

3.1. Demographic data of participants

Relevant participant characteristics are displayed in Table 1. The age of the participants ranged from 40 - 62 years and their experience in rice farming ranged from 15 - 49 years. Most participants wore 10.5" footwear. All participants exhibited excessive foot pronation identified by abnormal rear foot and medial longitudinal arch angles, as well as excessive knee valgus identified by abnormal Q or tibiofemoral angles.

Table 1. Participants characteristics

Characteristics	n (%)	Mean (SD)
Gender		
Male	4 (44.44)	
Female	5 (55.56)	
Age (years)		51.89 (6.86)
Height (cm)		161.78 (6.10)
Weight (kg)		59.80 (11.70)

Experience (years)		36.11 (9.71)
Size of footwear		
Size 10	1 (11.11)	
Size 10.5	6 (66.67)	
Size 11	2 (22.22)	
Rearfoot angle (deg)		10.70 (1.57)
Normal	0 (0)	
Abnormal	9 (100)	
Medial longitudinal arch angle (deg)		128.65 (2.38)
Normal	0 (0)	
Abnormal	9 (100)	
Q-angle (deg)		21.49 (1.88)
Normal	0 (0)	
Abnormal	9 (100)	
Tibiofemoral angle (deg)		170.82 (2.31)
Normal	0 (0)	
Abnormal	9 (100)	

3.2. Lower extremity alignment

The angle measurements for lower extremity alignment of participants are presented in Figs. 5-8.

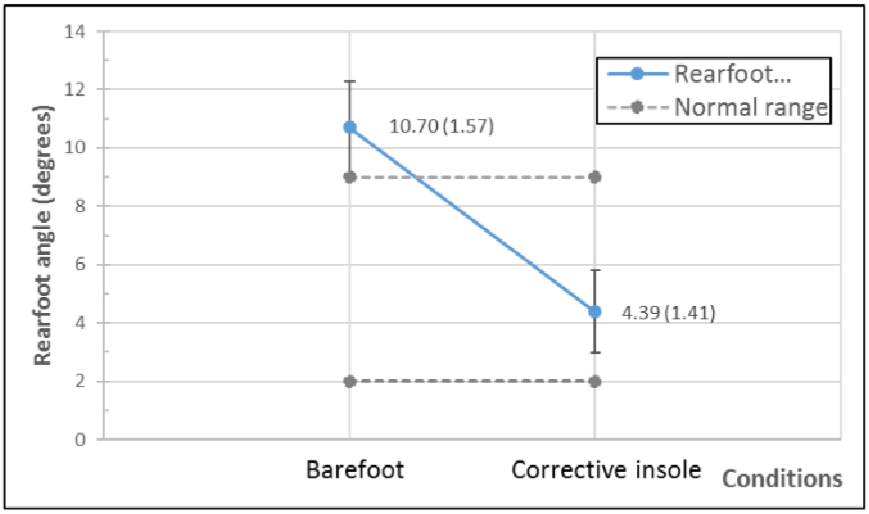


Fig. 5. Results of rearfoot angle alignment for rigid work terrain condition

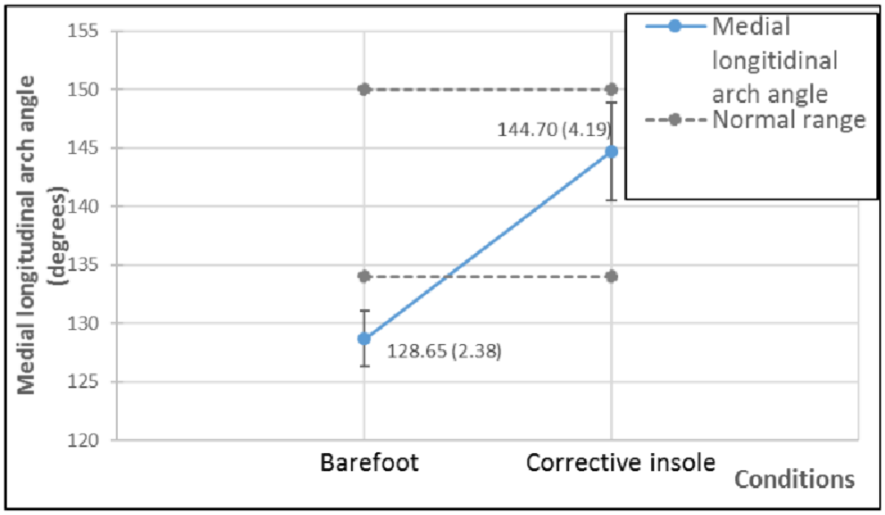


Fig. 6. Results of medial longitudinal arch angle alignment for rigid work terrain condition

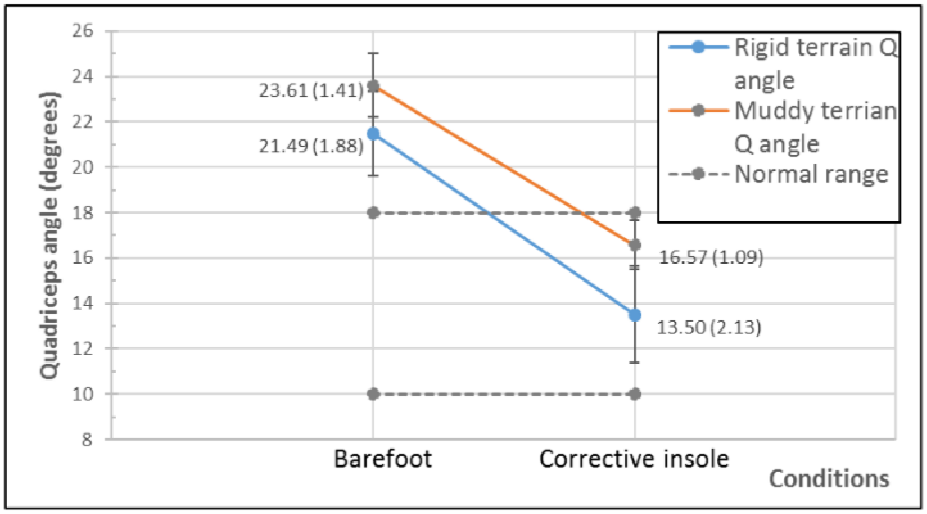


Fig. 7. Results of Q-angle alignment for various experimental terrain conditions

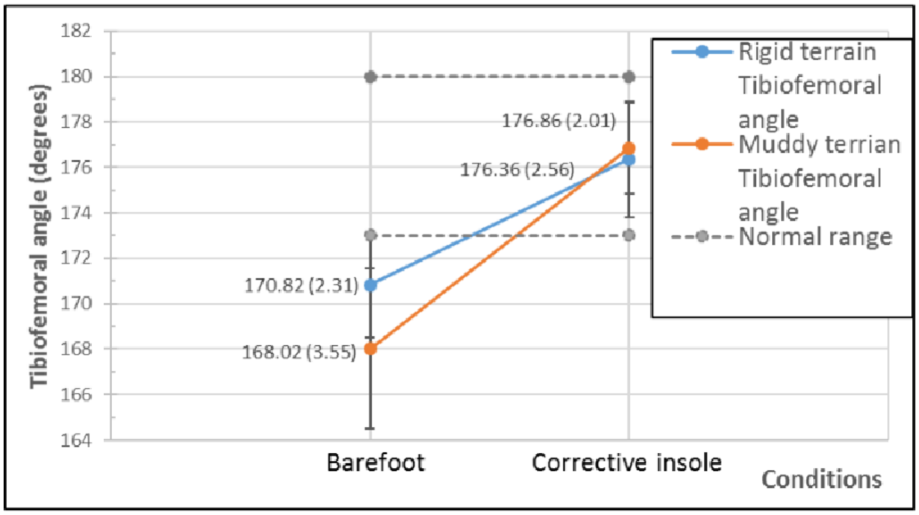


Fig. 8. Results of tibiofemoral angle alignment for various experimental terrain conditions

3.3. Lower extremity muscle activity

The comparison of PL and TA muscle activity between BF and CI conditions during standing on flat rigid and muddy terrains is presented in Table 2.

Table 2. Mean (SD) of muscle activity involved during flat and muddy terrain standing position

Muscle activity (%MVIC) (mean (SD))	Conditions			
	Barefoot (BF)		Corrective insole (CI)	
	Rigid terrain	Muddy terrain	Rigid terrain	Muddy terrain
Tibialis anterior (TA)	0.80 (0.22)	1.32 (0.20)	0.69 (0.19)	1.04 (0.21)
Peroneus longus (PL)	1.01 (0.19)	1.69 (0.16)	2.43 (0.23)	2.59 (0.41)

4. Discussion

4.1. Lower extremity alignment

Results show that the muddy terrain induced an increase in Q-angle for all participants (average increase of deviation of 0.5 – 2.8 degrees), likely due to the slippery surface posing a greater demand to control leg alignment. This situation may lead to postural instability and fatigue, therefore increasing foot and knee pain [37]. In agreement with expectation, participants showed abnormal alignments of the lower extremities when standing barefoot (BF condition) on both flat rigid ground and in muddy terrain. When the participants were equipped with corrective medial wedge insoles (CI condition), all lower extremity alignments showed less deviation (average improvement of 5.5 – 16.1 degrees) and could be identified as normal.

A number of corrective insoles have been investigated in previous studies. For example, studies that observed an average reduction in angles of foot eversion of 2.1-5.5 degrees during movement [27, 28] , whereas in the present study, rearfoot angles were reduced by approximately 6.3 degrees. This greater reduction might be due to differences in participant characteristics (older vs. younger participants), body movement (standing vs. walking or running), and material for fabrication of the insoles (rigid PLA vs. flexible Ethylene Vinyl Acetate (EVA)) compared to previous studies. Participant movement and use of less stiff material for insoles might result in less reduction in the degree of foot eversion. Moreover, the plastic wrap used to secure the insoles in the present study might have provided additional support over and above the corrective insoles, and may have altered the results of lower extremity alignment.

4.2. Lower extremity muscle activity

Results demonstrate that the muddy terrain resulted in greater activity of both invertor and evertor muscles, which indicates an attempt to increase muscular force to compensate for instability when standing in mud. For both terrain conditions, CIs induced lower TA muscle activity in agreement with our hypothesis. As an increase in contraction of the TA muscle contributes to deceleration of subtalar joint pronation moment [38], a decrease of TA muscle activity could be attributed to a successful CI intervention reducing foot pronation for both rigid and muddy terrain. Although a reduction of TA activity was clearly observed, differences were still relatively small, presumably due to the smooth low-friction surface of the PLA insole. Indeed, a previous study showed insoles with textured surface significantly decreased TA activity during stance phase [39]. Future development of wedge insoles should investigate the effects of textured surfaces, non-slip pads, or alternative materials on TA activity reduction.

Contrary to expectation, participants exhibited greater PL muscle activity when they stood on a CI as compared with the BF condition. Previous research indicates that a pronated foot structure is correlated with greater EMG amplitude for invertor muscles (e.g. TA) and less EMG amplitude for evertor muscles (e.g. PL), when compared to supinated or normal foot structures [18, 40]. The lower amplitude of the PL may be attributed to slight shortening of the muscle in the pronated position [16], limiting the range of motion and functional movement. The increase in mean activity of the PL muscle might reflect stretching, due to a lower degree of foot pronation when supported by a medial wedge insole. A previous study also reported an increase of PL maximum amplitude in asymptomatic participants with a medial wedge assisting lateral ankle stability, as compared to walking with common footwear [41].

5. Conclusions

The present study investigated the effects of simple corrective insoles on foot muscle activity as well as foot and knee alignments of farmers with pronated feet when they stood on rigid flat and muddy surfaces. A corrective medial wedge was selected for investigation due to its practicality for use by farmers in a rice paddy field, low production cost and time, and effectiveness in treatment of foot pronation. Corrective wedges were custom fabricated for each participant based on physical therapy assessment, 3D optical scanning and rapid prototyping techniques. The total time to complete the fabrication process was approximately 6 hours, which can be considered practical for custom-made products.

Results of the study showed that the muddy terrain induced greater deviation in knee alignments and produced increased activation of extrinsic foot muscles, which may result in fatigue for farmers. Therefore, working in muddy terrain is anticipated to increase lower extremity muscle pain and risk of injury. The proposed corrective insoles were found to help reduce TA muscle activity, which is necessary for decreasing foot pronation, in both muddy and rigid terrain conditions. The medial wedge insole also helped reduce foot pronation malalignment and served to stretch shortened PL muscles.

These findings demonstrate the positive effects of corrective insole usage on foot muscles and alignments for both rigid and muddy terrains. However, the relatively small number of rice farmers exhibiting foot pronation and participating in the study represents a limitation of the current work. Follow-up research is expected to include a greater number of participants, both with and without foot pronation, with the objective of identifying broadly effective methods for correcting and preventing common risks of lower extremity injury. Furthermore, the actual use of the corrective insoles for work will require some method to fix the insoles against the worker's feet (e.g., shoes, sandals, etc.). Such fixation methods will likely interact with the insoles to exert influence that will be different than just standing on the insoles as in this study. Future research will also include the development of assistive intervention techniques in the form of footwear for rice farmers, including custom insoles, to be worn while working under various work terrain conditions.

Brief sumary

What is already known

- The nature of work environment may cause healthy workers having performance worsening comparable to those of disabled people.
- The prevalence of MSDs among rice farmers in Thailand has been found very high.
- There are similarities in pain perception, malalignment, and origin of structural impairment between patients with cerebral palsy (CP) and rice farmers.

What this study adds

- The foot pronation and knee valgus improved when participants were equipped with corrective wedges.
- The wedges induced less tibialis anterior activity and greater peroneus longus activity compared to when participants were standing barefoot.
- The corrective insole usage demonstrated a positive effect to improve alignment and reduce invertor muscle force.

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We would like to acknowledge the participants of this study for their time.

Conflict of interests

The authors declare that they have no conflict of interests.

References

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