EFFECTS OF CUSTOM-MADE 3D PRINTED INSOLES FOR FLAT-FOOT PEOPLE ON GAIT PARAMETERS: A PRELIMINARY STUDY

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The purpose of this study was to make low-cost and custom-made 3D printed insoles for flat-foot people and to investigate the feasibility of these insoles in walking and running. Thirty people (15 normal and 15 flat-foot people) participated in this study. 3D scanner, 3D printer, and CAD software were used to produce insoles and motion capturing system and a force plate were used to perform gait analysis. Results indicated that custom-made 3D printed insoles were not effective on joint angles and ground reaction forces, but they affected the trajectory of COP positively during stance phase. Further study with different filling rate and materials of insoles are required to generalize 3D printed insoles for flat-foot people.

KEY WORDS: insoles, kinematics, gait, 3D printing, flatfoot

INTRODUCTION: In walking, the foot plays an important role in supporting weight. The functional structure of the foot is designed to move the body forward by the help of ground reaction forces so that the alignment of the foot could play an important role in standing and gait motions (Valmassy, 2006). The misalignment and/or dysfunction of a person's foot could affects the quality of his or her life. In these days, flat-foot patients are struggling with decreased impact absorption capacity of the foot, reduced foot control force, and excessive innate foot rotation (Arangio et al. 2004; Kitaoka et al., 1998) as the result of misalignment of tarsal bone and/or insufficient functions of plantar fascia.

There are a lot of insoles for flat-foot people in the field of rehabilitation, which are used for conservative treatment for foot deformity, chronic pain, and misalignment in musculoskeletal system. Most of these insoles are tailor-made and very expensive so that it is difficult for some people to access custom-made insoles with lower prices.

However, as a result of the increased popularity of 3D printers and low cost of 3D printing plastic materials, it is easy to produce diverse 3D printed objects with a custom-made design and cheap price.

The purposes of this study were to develop low-cost and custom-made insoles for flat-foot people with a 3D scanning and printing technique and to investigate the effects of custom-made 3D printed insoles on gait patterns of flat-foot people. Finally, this study wanted to check the feasibility of 3D printed insoles.

METHODS: Fifteen normal peoples (age: 22.73±4.18 years, height: 168.33±7.18 cm, mass: 66.86±6.38 kg) and matched fifteen flat-footed people (age: 22.87±2.61 years, height: 169.20±8.48 cm, mass: 63.92±7.17 kg) participated in this study. Flat-foot people were determined by the vertical drop (10mm above) using navicular drop test (Brody, 1982).

Hand-held scanner (EinScan-Pro, Hustem, Korea) were used to scan the foot segment of subjects in non-weight bearing situation. After scanning the foot, the 3D scanned file was filled, smoothed, and edited by using a commercial software (SculptGL®) prior to being sent to the 3D printer (Cubicon® 3DP-110F, Hyvision, Korea). The printer printed custom-made insoles in thermoplastic polyimide (TPI), layered at 2 microns. The filling rate of insoles was 15%.Then custom-made insoles were applied to each subject at standing posture. In weight-bearing and standing condition, we investigate subtalar joint angles (everted angle) and then attached extra wedge(s) (2°, 4°, and 6° wedges) on the bottom of printed insoles in order to make subtalar joint angle at standing be close to neutral position (Figure 1). After being made, custom-made insoles for flat-foot people were inserted in regular walking shoes (PU-241-1, Slazenger™, Korea) for gait experiments.

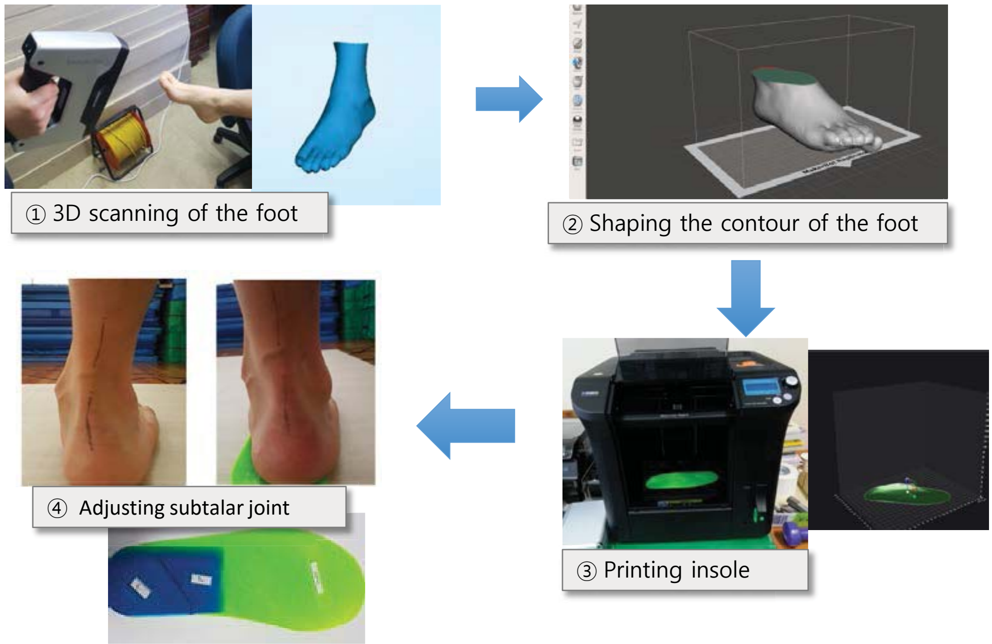

Figure 1: Procedure of making custom-made 3D printed insoles for flat-foot people

Both group subjects (normal people and flat-foot people) performed comfortable speed walking (0.83 to 1.11m/s), fast walking (1.11 to 1.38m/s), and running (1.38 to 1.66m/s), respectively, on the 10m walkway having a force platform (BP400600-OP, AMTI®, USA) and motion capturing system. The motion capturing system consisted of five high speed camera (Osprey®, Motion Analysis Inc., USA) with a sampling rate of 120Hz and an operating software (Cortex® 5.0, Motion Analysis Inc., USA). Normal people used same shoes (PU-241-1, Slazenger™, Korea) with built-in insoles but flat-foot people did them with custom-made insoles inside of shoes. The reflective markers were attached on the shank and foot segments to obtain 3D joint angles and joint moments (flexion/extension, inversion/eversion, adduction/abduction). The center of pressure (COP) and ground reaction forces were recorded by the force platform. Calculation of kinematic variables were performed on Cortex®. All subjects performed five repeated trials at each condition. The ensemble averages of each subject and each condition were calculated. Three group results such as people of normal, flat-foot, flat-foot with 3D printed insoles were compared only during the stance phase of the gait.

RESULTS: There were non-significant differences in flexion/extension angles between different groups across comfortable walking, fast walking, and running. Regarding inversion/eversion angles, there were significant different patterns between normal and flat-foot people. Flat-foot people revealed continuous inverted angles through stance phase, while normal people showed changes from eversion to inversion. The custom-made 3D printed insoles for flat-foot people slightly changed the pattern of inversion/eversion angle, shifting it toward inversion but non-significant (Figure 2).

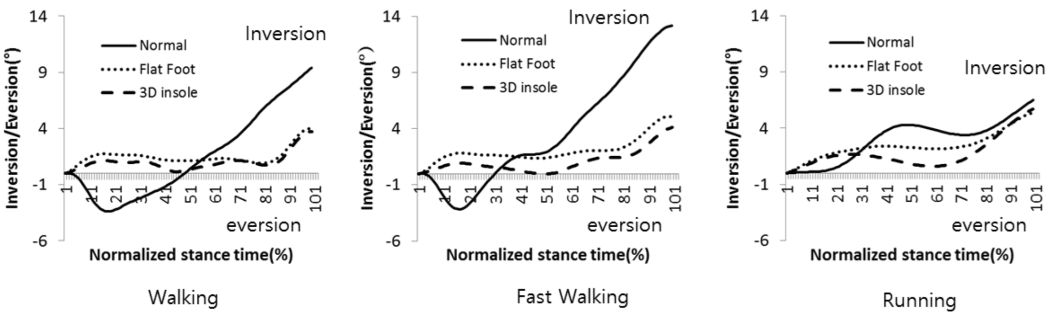

Figure 2: Comparison of inversion/eversion angles at different gait speeds during stance time. Normal and flat-foot people and flat-foot with 3D printed insoles conditions were compared.

About the COP trajectory, there were distinctive different patterns between normal and flat-foot people at normalized stance phase. The COP trajectory of flat-foot people was medially deviated from the baseline (heel to toe line). However, the 3D printed insoles for flat-foot people improved the COP significantly close to the pattern of normal people in walking and fast walking. The effect of insoles on the COP trajectory in running was weak, indicating less shift of the COP laterally (Figure 3).

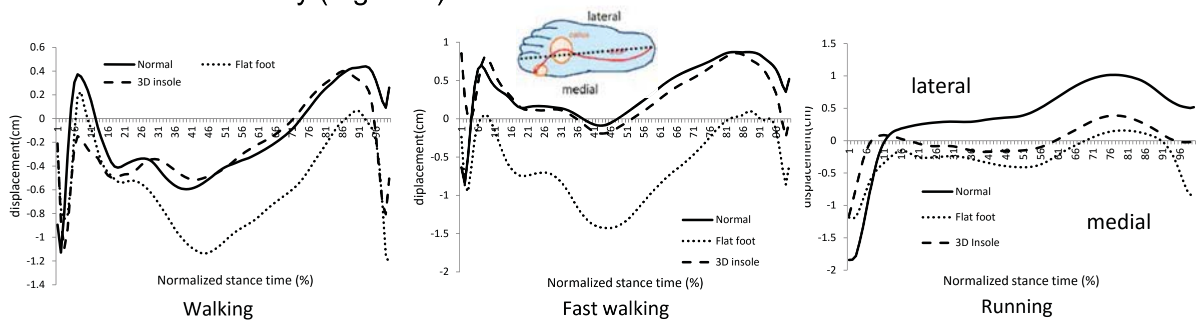

Figure 3: Comparisons of COP trajectory during normalize stance phase according to different gait speeds among normal, flat-foot people, and flat-foot people with 3D printed insoles. The deviation of COP was defined as medial or lateral movement from the baseline (heel to toe connected line).

Regarding ground reaction force (GRF), the flat-foot people revealed slightly higher normal GRF than normal people at walking and running conditions across normalized stance phase. The custom-made 3D printed insoles slightly reduced normal GRF during only mid-stance points but did not significantly change GRF profiles except mid-stance points for flat-foot people (Figure 4). In running, the 3D printed insoles seemed to give no effect on the normal GRF profiles.

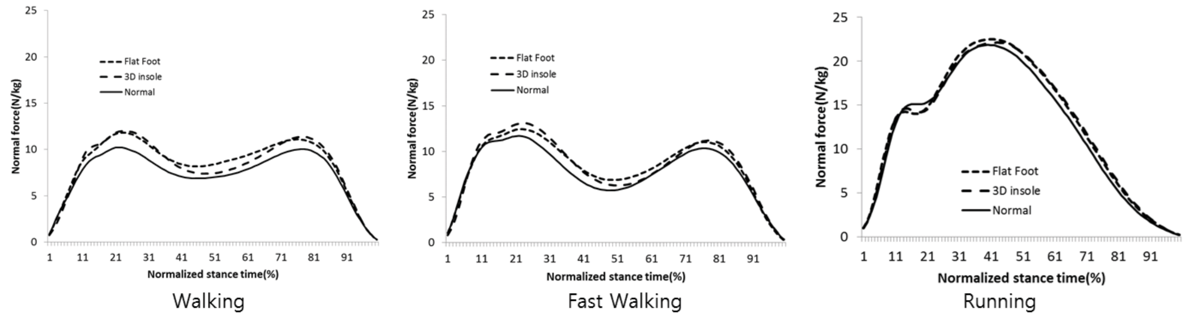

Figure 4: Comparison of normalized ground reaction forces during normalized stance phase according to different gait speeds among normal, flat-foot, and flat-foot people with 3D custom-made insoles.

DISCUSSION: Custom-made foot orthoses are currently considered as a gold standard of non-surgical treatment for foot and lower limb pathology, offering the benefits of individualized prescription. However, it costs a high price relatively so that some people could not use this option. This study was purposed to investigate the feasibility of low-cost and custom-made 3D printed insoles for flat-foot people.

Results indicated that there were significantly difference in gait patterns and parameters between normal people and flat-foot people for inversion/eversion angles and the COP. Flat-foot people showed restricted motions of inversion and eversion due to drop of navicular bone. When custom-made 3D printed insoles were applied to flat-foot people, there was no distinctive effect on joint angles and ground reaction forces. However, the trajectory of COP was significantly changed as a result of 3D printed insoles.

The COP is a very important parameter associated with osteoarthritis (OA). Gait parameters from the distal segment such as the foot center of pressure (COP) are related to symptomatic knee OA with a larger shift in the foot COP as compared to normal people (Baliunas et al., 2002). By the help of custom-made 3D printed insole, the trace of COP was shifted laterally. This could reduce abnormal stress on knee joint and upcoming pains of the lower limb. As well this could be accorded with Zhai et al. (2016)'s results, indicating reduced the plantar pressure by the help of orthotics. Since flat-foot people lose the arch in a load-bearing condition, the support of the arch by the custom-made insoles could give less stresses on the plantar fascia and result in lower plantar pressure (Pauk & Ezerskiy, 2011).
Regarding the feasibility of custom-made 3D printed insoles for flat-foot people, there are still some issues. In order to improve the quality of insoles, it is necessary to consider the printing materials and durability of insoles further. Since the mechanical property of insoles such as cushioning drop and flexed position significantly depends on the filling rate and the selection of materials of insoles, those factors should be optimized to individuals further.

CONCLUSION: This study investigated the feasibility of low cost and custom-made 3D printed insole for flat-foot people in walking and running in order to substitute high cost orthoses. Even though there was no significant change in joint angles and ground reaction forces, the custom-made 3D printed insoles significantly improved the trace of COP laterally. Further study associated with insole materials and filling rates are need to produce low-cost and good-quality custom-made insoles for flat-foot people.

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