A Smart Pressure-Sensitive Insole that Reminds You to Walk Correctly: An Orthotic-less Treatment for Over Pronation

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Abstract—**We equipped an insole with a force sensor that can detect in real time when a foot over pronates. When such behavior is detected, we warn the user so they can correct their posture by using their own muscles. The effectiveness of this novel way to correct over pronation posture is evaluated over a two-week period. The use of vibrotactile feedback reduces over pronation by 30% to 50% during the first week. The natural benefits of the proposed method vs. use of passive orthotics are also presented.**

I. Introduction: Calcaneal inversion and Fashion

Use of modern Western footwear and particularly pointed narrow toe-box shoes popularized by sportswear and fashion brands during the second half of the 20st Century, is correlated with a high prevalence of foot deformities that are virtually non-existent in barefoot cultures in South Africa, South America and Nepal. For example, Hallux Valgus (HV) has an estimated prevalence in the United States of 23% to 35%. However, less than 5% of the African population suffers HV [1-5]. Conditions correlated with the use of modern pointy footwear are: (i) flat feet or fallen arches, (ii) HV, (iii) plantar fasciitis (fasciosis), and (iv) calcaneal inversion. The common root cause of these conditions is in general an abnormal foot posture, which is reflected in a disconnected pressure footprint.

When footwear pushes the big toe inwards, the tripod formed by the big toe, the fifth toe and the heel is narrowed in the shortest side causing instability. This geometry makes it easier for the foot to over pronate. On the other hand, if the toes are allowed to spread to their natural width the foot is more stable. A healthy arch and a stable big toe make over pronation mechanically impossible. While, there are no comprehensive studies on calcaneal inversion prevalence, this condition is often accompanied by: HV, over pronation, lower arches (due to over pronation), a callus on the outer side of the big toe, a disconnected pressure footprint, increased pressure on the first toe (100% increase), and sometimes sesamoiditis.

Orthotic heel wedge insoles are typically prescribed to correct the calcaneal inversion and accompanying over pronation. The use of orthotics results in an apparent correction of the foot posture that always results in restoration of a healthy pressure footprint. However, we claim that orthotics has a drawback: they are passive and thus the resulting foot arch shape might not come as a result of the patients own muscles (as is the case in barefoot people). If such muscles are not exercised because the foot rests on top of a comfortable orthotic shape, they lose strength and consequently their beneficial functions of protective shock absorption, efficient gait [6] and other complex functions, as recently shown by [7] become impaired. In this work we present an over pronation and calcaneal inversion correction system that is based on active retraining of the foot muscle.

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II. Orthotic-less Treatment By Bio-feedback

Fig. 1 shows an insole inspired by the quantified-self lifestyle trend, pioneered by products such as *Fitbit*TM, *Nike*+TM and the *Bioness*TM foot drop system. As with the *JawboneUP*TM wristband, it provides feedback by means of vibration.

A. System Design

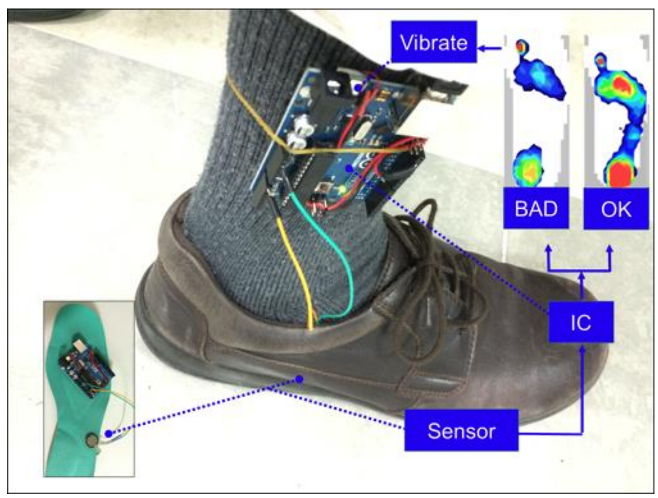

Figure 1. The biofeedback insole is comprised of a pressure sensor, one Arduino board, one USB battery and a resistive force sensor mounted on the outer midsole position. A tiny vibrator from a mobile phone (mounted on the back of the board) warns users when they over pronate.

The device warns the patient whenever an “unhealthy” posture is detected for longer than 10s, hence alerting the patient for the need to readjust their foot alignment.

Vibrotacticle feedback has been previously applied to balance training [8-9]. Surprisingly, it has never been applied to correct the foot posture. Consequently, the goal here is for the patients to train themselves to walk properly based on the biofeedback. Fig. 2 illustrates how foot over pronation and inversion is indirectly detected by monitoring pressure with a sensor placed in the outer midsole. This particular position was chosen because it offers the most pressure discrimination range and robustness to noise.

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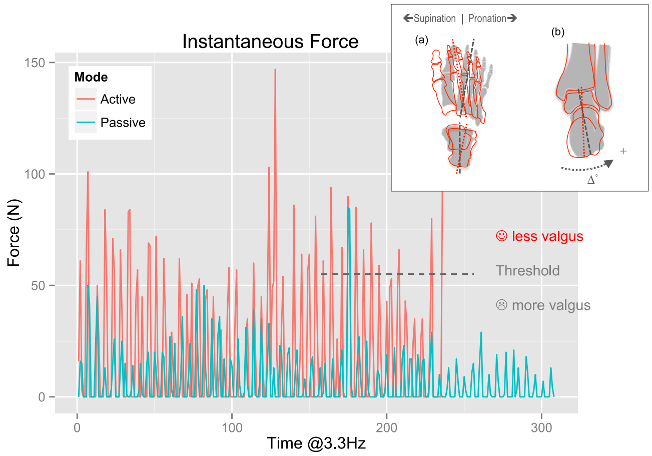


Figure 2. Instantaneous force sensor reading at outer midsole point of an untrained subject. Passive: valgus walk. Active: the patient is instructed to walk while actively correcting valgus (calcaneal inversion) posture by using foot muscles. A force threshold can be set to discriminate healthy from unhealthy postures. (a) Plantar view. (b) Δ is calcaneal inversion in degrees. Top right adapted from [6].

B. Calibration

Each patient suffering inversion was verbally instructed to adopt a valgus free posture by a doctor by means of the foot arching method. To assess the inversion degree of a given foot posture we chose to measure the inversion (Δ) and the connectedness of the pressure foot print shape.

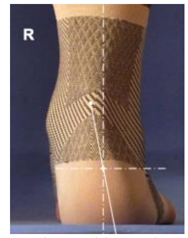
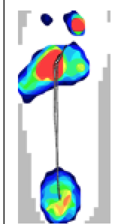
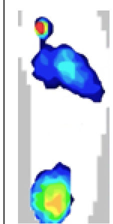
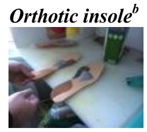
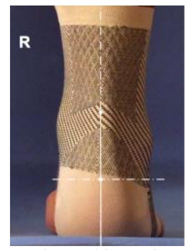
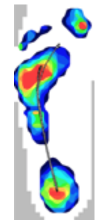
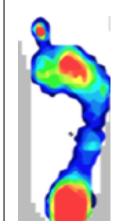
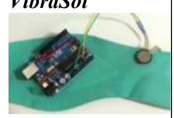
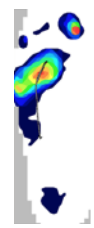
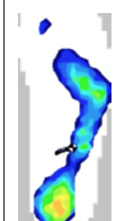
A foot posture was deemed healthy when Δ=0˚. The correlation between inversion and footprint shape is very high. Additionally, we observed (N=11) that inversion is always coupled to a disconnected pressure footprint. Therefore, to detect calcaneal inversion it suffices to place a single force sensor in the region that becomes disconnected when a patient switches from healthy to valgus or pronation posture (see Table I).

To visualize footprints an *F-Scan Research 6.70* sensor matrix mat, that users step on, was used. The force sensor used was a TekScan Silver FlexiForce A401. This sensor is a fairly linear resistive force sensor from which pressure can be deducted by dividing by the sensor area, which naturally is constant.

C. Alert Threshold & False Positive Avoidance

During walking and normal daily life activities, the pressure pattern varies greatly with the activity. To avoid false positives, a heuristic rule of thumb is to warn the user if the threshold pressure is not reached for more than 10s. In other words, when the user walks we alert him roughly, if more than four steps (about 10s) have not reached a threshold pressure reading that indicates healthy connected footprint. (See Annex for details on signal processing and warning logic.) Fig. 2 shows the instantaneous force on the sensor for a patient suffering severe calcaneal inversion. The patient was instructed to walk normally and then to walk actively trying to avoid inversion. Table I, compares this correction method with a wedge orthotic treatment.

TABLE I. COMPARISON OF TWO TREATMENTS FOR CALCANEAL INVERSION: BIOFEEDBACK VS. ORTHOTICS

Correction method	***Posture***	***Pressure footprint case***	
		Walk[a] ***(L foot)***	***Standing (R Foot)***
None (Barefoot) Pronation $\Delta = +9.5^{\circ}$ Muscle: Passive	 Calcaneal inversion (Severe deviation)		
Orthotic insole[b]  Pronation $\Delta = 0^{\circ}$ Muscle: Passive	 Calcaneal inversion corrected by orthotics		
Biofeedback VibraSol[d]  Pronation $\Delta = 0^{\circ}$ Muscle: Active	 Inversion corrected actively by user		

a. F-Scan center of pressure path.

D. Vibrotactile Feedback

As discussed earlier, appropriate warning logic ensures low false positive rate due to normal daily life activities such as: overreaching to grasp an object or other dynamic positions (playing basketball, hugging a friend or changing walk direction). As biofeedback, a standard pancake phone vibrator was used in contact with the lower leg. As alert for over-pronation two vibration pulses of 1 second length each were chosen because in Japanese the word 'no' contains two syllables. No other feedback is given because some patients reported it as confusing. The force sensor is placed under the shoe insole, not on top because while it is flexible, it broke down often with normal wear and tear. Under-the-insole placement decreases the sensitivity but in our application it is an acceptable trade-off. An Arduino UNO was used as a control & data acquisition unit.

E. Data Points Log

The sensor is sampled at 3.33Hz. Every 150s, we log a *data point* that consists of: number of steps, mean and standard deviation of force, number of warnings issued to patient and a simplified histogram of force for the last 150s. Given 1kB of

EEPROM available, the recording capacity is 4.61 hours. Afterwards, the data can be downloaded to the doctor's computer via an USB cable.

III. CASE STUDIES

A. Case I: Severe inversion

A 37 year old Caucasian male was diagnosed with severe inversion (Δ = +9.5˚). Additionally, his footbridge had collapsed since childhood, causing his ankle to lean inwards (valgus) and his toes to misalign outwards. Severe hallux valgus was present. This resulted in a typical disconnected pressure footprint (Table I). The podiatrist prescribed custom-made insoles to correct the posture that included various wedges and pads. The insole achieved a realignment of the toes and improved the footprint fitness, achieving a healthy footprint when worn (Table I). To evaluate the effectiveness of the proposed correction method based on vibrotactile feedback, we replaced the prescribed orthotic insole with the smart insole on the right foot and calibrated it to vibrate the patient when over-pronation was detected as illustrated in Fig. 1.

B. Case II: Mild inversion

A 25 year old Caucasian male was diagnosed with mild inversion Δ =+0.8˚, no bunions and mild hallux valgus was observed.

C. Data Logging

On day 1, the subject receives a device and instructions on how to correct their valgus posture. As described earlier, the device is calibrated to warn if over-pronation is detected. On random days, warnings are deactivated to evaluate the progress of the training. Combining data from the previous two cases and other shorter tests, over 2,140 data points were collected during two weeks of data logging corresponding to 5,350 minutes. As described in section I, each data point represents 150s of sampling time.

D. Effect On Posture

Figs. 3, 4 compare the effect of biofeedback and walk speed on foot pronation. It shows a scatter plot of data points where X-axis is the walk speed average (step count) for each data point. Y-axis is the proportion of time where over-pronation was detected (in 4 bit resolution scale.)

E. Learning Curve

Fig. 5 shows the evolution of posture correctness by elapsed training days. Figs. 6, 7 indicate how patients posture evolve in the first week.

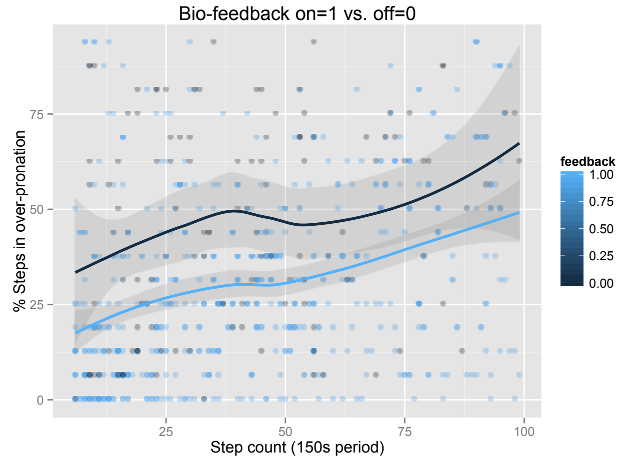


Figure 3. Progress of training. Light blue line is scatter of over-prontion % vs. steps, when feedback is on. Dark blue orresponds to feedback off. Turning feedback off increases over-pronation by 30% to 50%.

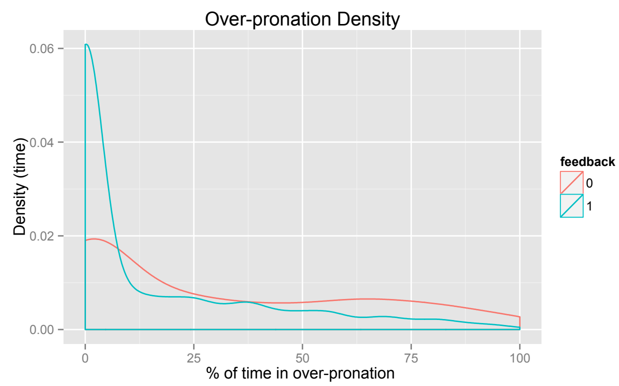


Figure 4. Comparison of over-pronation density graphs for data points with feedback on (1), off (0). Turning feedback off during the first week of training increases the proportion of unhealthy postures detected

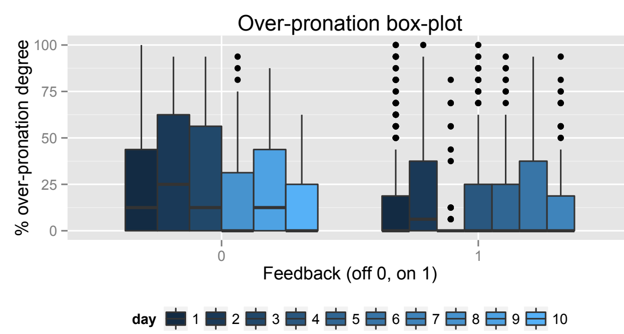


Figure 5. Evolution of the pronation on a daily basis. Left: are periods when vibration feedback is OFF. Right: represent periods with feedback ON.

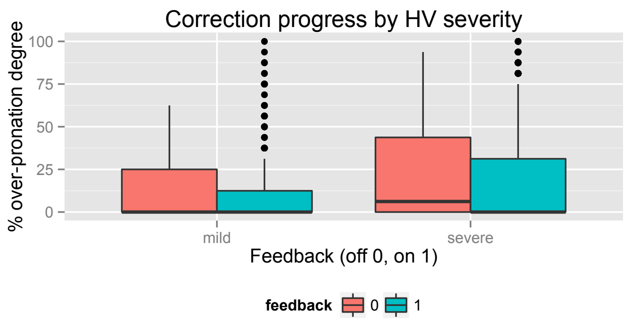


Figure 6. Correction progress for the first week of training according to valgus diagnosis severity.

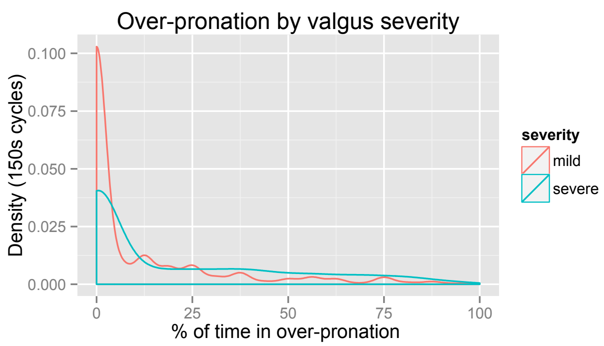


Figure 7. Patient with mild valgus corrects faster than patient with severe HV. First week of trainning. Data points for feedback on.

IV. Discussion of Results

A. *Effectiveness*

Figs. 3, 4 show that use of vibrotacticle alerts can help reduce between 30% to 50% of the time a patient spends in damaging over-pronating postures. Interestingly, when the feedback is turned off the patients revert to the old walking style but not completely (training effect).

B. *Self-perception of Footprint*

The patients in the case study, as well as 11 other candidates whose valgus degree had been considered, confirm that regardless of valgus degree, patients believe that their current walking posture is correct due to a strong self-image. Consequently, posture correction from valgus to non-valgus, results in an initial perception of wrong posture by the patient.

C. *Learning Curve*

Figs. 5, 6 confirm the trend that over-pronation slowly decreases with each training day. During the first week, with feedback on, the device helps reduce over-pronation time significantly as compared to feedback off. For patients with high inversion deformity, it is strenuous to regain a healthy footprint without the help of orthotics. A combination of orthotics and vibrotactile feedback seems appropriate. Pain resulting from the readjustment of the spinal column, particularly the cervical vertebrae to the new walking posture must also be taken into account and managed. On the other hand, the results of the mild valgus case indicate that an almost complete correction of the valgus posture (<10%) is possible if feedback is kept on.

V. Conclusion & Future Works

We have introduced an interactive insole that assists the patients to correct calcaneal inversion by means of vibrotactile feedback. Compared to relying on remembering verbal instructions alone, adding constant real-time feedback helps the patient to reduce unhealthy posture time by 50%.

Notwithstanding the results, the prototype in its current form factor is inconvenient to use. On the other hand, producing a professional wearable is costly. Therefore we developed a 3D printed mechanical-only arch support that has a protuberance in the center (a pain capsule). Its function is to create a straightforward discomfort level proportional to the pronation level. We are currently running an N=50 trial in UAE and Ireland.

Appendix

The source code is available at http://github.com/vibrasol/

Acknowledgment

The author thanks Gerald Baudrillard podiatrist at Al Noor hospital Abu Dhabi, Tiago Caldeira of KUSTAR and Triona Coppinger.

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