A three-pressure-sensor (3PS) system for monitoring ankle supination torque during sport motions

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Editor of Journal of Biomechanics,

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The authors declare no financial and personal relationships with other people or organizations that could inappropriately influence this submitted work.

Daniel Tik-Pui FONG
Dec 18th, 2007.

* **Cover Letter**

Cover letter

Editor of Journal of Biomechanics,

REF: Submission of manuscript "A three-pressure-sensor (3PS) system for monitoring ankle supination torque during sport motions"

The authors would like to submit this paper as an "Original Article". We declare that each author were fully involved in the study and preparation of the manuscript and that the material within has not been and will not be submitted for publication elsewhere.

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Daniel Fong

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Dec 18th, 2007.

* Manuscript

Title Page

Title	A three-pressure-sensor (3PS) system for monitoring ankle supination torque during sport motions		
Article type	Original Article		
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A three-pressure-sensor (3PS) system for monitoring ankle supination torque during sport motions

Abstract

This study presented a three-pressure-sensor (3PS) system for monitoring ankle supination torque during sport motions. Five male subjects wore a pair of cloth sport shoes and performed ten trials of walking, running, cutting, vertical jump-landing and stepping-down motions in a random sequence. A pair of pressure insoles (Novel Pedar model W, Germany) was inserted in the shoes for the measurement of plantar pressure at 100 Hz. The ankle joint torque was calculated by a standard lower extremity inverse dynamic calculation procedure with the data obtained by a motion capture system (VICON, UK) and a force plate (AMTI, USA), and was presented in a supination/pronation plane with an oblique axis of rotation at the ankle joint. Stepwise linear regression analysis suggested that pressure data at three locations beneath the foot were essential for reconstructing the ankle supination torque. Another group of five male subjects participated in a validation test with the same procedure, but with the pressure insoles replaced by the 3PS system. Estimated ankle supination torque was calculated from the equation developed by the regression analysis. Results suggested that the correlation between the standard and estimated data was high (R = 0.938). The overall root mean square error was 6.91Nm, which was about 6% of the peak values recorded in the five sport motions (113Nm). With the good estimation accuracy, tiny size and inexpensive cost, the 3PS system is readily available to be implanted in sport shoe for the estimation and monitoring of ankle supination torque during dynamic sport motions.

Keywords: Ankle sprain, biomechanics, joint moment, kinetics, inversion

Introduction

Ankle sprain is a common sport injury (Fong et al., 2007a) which may lead to ankle instability (Yeung et al, 1994). In a recent world consensus conference on ankle instability in September 2004, over twenty world renowned orthopaedic specialists concluded that there was still no general consensus to treat ankle instability (Chan and Karlsson, 2005). The experts added that instead of paying tremendous effort in treating ankle instability, the prevention of ankle sprain injury would be the appropriate research direction in solving the problem.

Different prophylactic approaches were employed to prevent ankle sprain injury, however, the prevalence is currently still significant. A recent epidemiology study showed that ankle sprain injury is still a common sport-related trauma, accounting for 12% of all attendance in an accident and emergency department (Fong et al, in press). This suggested a room for alternative measures for preventing ankle sprain injury in sports. Recently, there is an innovative attempt to design an intelligent "sprain-free sport shoe" for the purpose (Chan, 2006). The shoe first senses the ankle supination torque, then identifies if there is a significant injury risk, and finally initiated corrective action to protect the ankle joint. This study presented a three-pressure-sensor (3PS) system which serves the purpose to monitor the ankle supination torque during sport motions.

Method

Development test

Five right-legged male subjects (age = 23.0 ± 3.0 yr, height = 1.72 ± 0.03 m, body mass = 65.1 ± 9.7 kg, foot length = 255-260 mm) wore a pair of cloth sport shoes

(Fong et al., 2007b) and performed ten trials of walking, running, 45-degree cutting, vertical jump-landing and stepping-down (from a block) motions in a random sequence in a biomechanics laboratory. The university ethics committee approved the study. Twelve reflective markers were attached at the hallux, distal first metatarsal, distal fifth metatarsal, proximal first metatarsal, proximal fifth metatarsal, navicular, medial calcaneus, lateral calcaneus, heel, lateral malleolus, tibial tubercle, and lateral femoral epicondyle, either on the skin or shoe surface. The essential anthropometric data was measured by an anthropometer for the ankle joint torque calculations (Vaughan et al., 1992). A pair of pressure insoles (Novel Pedar model W, Germany) was used for measuring the plantar pressure at 99 positions covering the whole plantar area at 100 Hz. Each subject performed the motion and stepped with their right foot on a force plate (Advanced Mechanical Technology Inc., USA), which sampled the data at 1000 Hz.

The collected data were trimmed from the moment of take off before the foot strike on the force plate, until the next take off from the force plate. For jump-landing and stepping-down motions, the data was trimmed until one second after the foot strike as there was no another take off. The force plate data were re-sampled to every 0.01s to match the frequency of the pressure data. The ankle joint torque was calculated by a standard lower extremity inverse dynamic calculation procedure (Vaughan et al., 1992). The torque was presented in a supination/pronation plane with an oblique rotation axis tilting 42 degrees upward and 23 degrees medially from the perpendicular axes of the foot (Hertel, 2002). Resultant linear acceleration at nine positions (hallux, distal first metatarsal, distal fifth metatarsal, proximal first metatarsal, proximal fifth metatarsal, navicular, medial calcaneus, lateral calcaneus, heel), and the resultant angular velocity at the foot segment center of mass were obtained from the motion capture system (VICON, UK).

Data from all trials, all motions and all subjects were pooled together for stepwise linear regression analysis to reconstruct the value of the ankle supination torque (SupT) by the value of the 99 pressure sensors (P1, P2, …, P99, unit = N/cm^2), the resultant linear acceleration at the nine positions (unit = m/s^2), and the resultant angular velocity at the foot segment center of mass (unit = deg/s). A linear regression was performed as a linear relationship was expected between the ankle supination torque and each of these predictors. In each analysis, predictors were added to the regression models until the inclusion of the next predictor showed redundancy, as indicated by a tolerance value of less than 0.20.

The analysis suggested that only three pressure data (Figure 1) were essential to reconstruct the ankle supination torque, with an explained variance of 0.831 (adjusted R^2). The three locations were approximately at the fourth/fifth metatarsalphalangeal joint (Position 60), the third metatarsalphalangeal joint (Position 72), and the second/third distal phalange (Position 98). The linear acceleration and angular velocity were not essential. The regression model is shown as follow, with PX as the value of pressure of the sensor at position X, in N/cm^2.

$$SupT\ (Nm) = -2.068 + 0.910 \times (P60) + 1.318 \times (P72) + 1.549 \times (P98) + error$$

Validation test

A three-pressure-sensor (3PS) system (Sengital, Hong Kong) with three individual circular pressure sensors (Interlink Electronics, Force Sensing Resistor Model 400, USA) implanted to the three positions beneath an insole in a sport shoe (Dr Kong Footcare Limited, C70135) was fabricated (Figure 1b-d). The pressure sensors were 5.0mm in diameter and 0.30mm in thickness, and the price of each sensor was about US 1-2 dollars. The instrumented insole was calibrated with a pressure calibration device (Novel Trublu, Germany) in the range of 0-60 N/cm^2 (Figure 2). The pressure sensors output a 10-bit digital signal (0-1023), and the calculation of the estimated ankle supination torque ($SupT_{estimated}$) is represented by the following equation, with SX as the sensor signal at position X (unit-less, range = 0-1023).

$$SupT_{estimated}\,(Nm) = -2.068 + 0.00190827\, e^{0.01252(1023-S60)} + 0.002763846\, e^{0.01252(1023-S72)} + 0.003248253\, e^{0.01252(1023-S98)}$$

Another group of five right-legged male subjects (age = 23.8 ± 3.3 yr, height = 1.74 ± 0.03 m, body mass = 65.4 ± 7.3 kg, foot length = 255-260 mm) participated in the validation test. Independent t-tests showed that the two groups of subjects did not differ in age, height and body mass ($p > 0.05$). The same procedure in the development experiment was conducted, with only the 99-sensor pressure insoles replaced by the 3PS system to estimate the ankle supination torque ($SupT_{estimated}$). Data from all trials were pooled together, and the correlation coefficient (R) and the root mean square error (RMS error) were computed between the standard (SupT) and estimated data ($SupT_{estimated}$).

Results

Table 1 shows the good accuracy of the ankle supination torque estimation. The correlation was high in most individual motion and subject (R > 0.80). In overall, the correlation between the standard and estimated data was 0.938. The overall RMS error was 6.91Nm, which was about 6% of the peak values recorded in the motions (113Nm).

Figure 3 shows the pattern and the absolute error of the standard and estimated data of one selected trial in each motion, which has an average accuracy among all trials. In general, the estimated data followed the pattern of the standard data well, even for the instable period during the first 0.40s after landing in cutting motion. The estimation was in-phase during the fluctuating period, indicating that the 3PS system is sensitive to the trend of changes. The peak magnitudes of the estimated values were about 95-105% of that of the standard data in all motions, indicating a very good estimation of the peak values.

Discussion

Forner Cordero and coworkers presented a method to calculate joint torque from limited ground reaction force information from pressure insoles (Forner Cordero et al., 2004, 2006). They reported very good accuracy in calculating ankle joint torque, as indicated by a small RMS error (3.177Nm to 5.758Nm). In this study, although the accuracy is slightly inferior, the new method involves only three individual pressure sensors and does not rely on motion capture system, and is readily available to be implanted in a sport shoe for real-time ankle supination torque measurement.

In this study, two groups of similar subjects were recruited to limit the variability of the nature of subject, in order to test the feasibility of the presented method. Future studies are necessary to generalize the method to other subject groups, or to establish different methods for different subject groups. Besides, even within a homogeneous group of subject, the supination-pronation axis may still vary among each individual (Lundberg et al, 1989). This has to be considered in real application of the presented method. Another limitation is the lack of a spraining motion being tested. Including a spraining motion in laboratory would be unethical and also practically impossible. To cope with this, we intended to select five representative motions in most sports, especially in cutting and jump-landing motions which most commonly involve ankle sprain injury. Yet we may not be able to estimate the ankle supination torque during a real sprain, we could monitor the magnitude and check if it is approaching to injury. Future studies should contribute by suggesting an ankle supination torque threshold in order to identify significant ankle sprain risk.

This study presented a three-pressure-sensor (3PS) system that could estimate the ankle supination torque during various dynamic sport motions with good accuracy. The system is inexpensive and tiny, and could be implanted into a sport shoe. The device serves as a platform for a recently developed "sprain-free sport shoe" for real-time monitoring of ankle supination torque and the subsequent ankle sprain injury risk.

Acknowledgement

This study was financially supported by the Innovation Technology Fund from the Innovation and Technology Commission, Hong Kong Special Administrative Region Government, Project Number: ITS/015/06. The authors acknowledge Dr Alan Hiu-Fung Lam and Mr Joe Chi-Yin Wong of Sengital Limited to provide technical assistance in the development of the three-pressure-sensor (3PS) system for this study.

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* Revision Notes

Date: 09-04-2008
To: "Kai-Ming Chan" kaimingchan@cuhk.edu.hk
From: "Journal of Biomechanics" JBM@elsevier.com
Subject: BM-D-07-00917 - Editor Decision
Ref.: Ms. No. BM-D-07-00917
A three-pressure-sensor (3PS) system for monitoring ankle supination torque during sport motions
Journal of Biomechanics

Dear Professor Chan,

Thank you for your submission to the Journal of Biomechanics. After considering the enclosed reviews from our referees, I regret to inform you that our referee panel recommends against publication of your manuscript in its current form, although a revised manuscript may be resubmitted and considered after further review. Although it is obvious your manuscript represents considerable work, and the referees and I believe it to be relevant to the Journal, the referees raised several major issues that would need to be addressed prior to publication. In general, the referees were enthusiastic about the potential of your study, but raised several major concerns. Their comments are attached for your information.

Perhaps most importantly is whether your work is published as an Original Article or a Short Communication. Published guidelines state Original Articles "typically explore some explicit biological hypothesis or report original but substantial observations or data of broad utility. Conceptually but novel experimental or computational methods may be submitted as Original Articles when their relevance and importance for research or biological questions is demonstrated or otherwise emphasized in the text." A Short Communication, on the other hand reports "preliminary observations, simple new techniques or devices, calibrations/validations, or points of historical interest." Currently, your material best fits the guidelines of a "Short Communication". My sense from the reviewers is that without additional data, your manuscript should be reformatted to adhere to the guidelines for a short communication (<1500 words, 3-4 figures).

Please note that in consideration of the authors' and the reviewers' time, I normally allow only one major revision; if the reviewers request another major revision, I regret that we will not be able to publish your manuscript. Unfortunately, we have been forced to decrease our acceptance rate significantly due to an increase in manuscript submissions.

To submit a revision, go to <http://ees.elsevier.com/bm/>http://ees.elsevier.com/bm/ and log in as an Author. You will see a menu item called Submission Needing Revision. You will find your submission record there. Please update accordingly and submit your revised manuscript."

If you choose to submit a revised manuscript, please provide a list of points of how you have responded to the reviewers' suggestions with the revised manuscript, at your earliest convenience. If you do not wish to proceed, please let us know in order to complete our records. The maximum time allowed for revision is 8 weeks, after which the file on this manuscript will be closed. If you feel you need longer than this please contact me.

Please note:

* Any figures and tables should be included, even if these are unaltered.
* It is the author's responsibility to ensure that data presented in figures and tables agree with that provided in the text. Please cross check figures, tables and text carefully.
* Please double-check formatting of your references
* Please use your word processor to automatically number the lines of your manuscript

Thank you again for submitting to the Journal of Biomechanics. I look forward to receiving your revised manuscript.

Yours sincerely,

Farshid Guilak, Ph.D.
Editor-in-Chief
Journal of Biomechanics

Reviewers' comments:

Reviewer #1: Summary

The manuscript presents a new method for measuring ankle supination torque during sport activities using the 3PS. Two studies are presented: a development study, during which plantar pressures and ankle joint torques were sampled in five subjects using pressure insole and optoelectronic tracking + forceplate during several sports motions, and a validation study, during which the same experimentation was repeated in another group of five subjects, replacing the insole by the 3PS. The results show a good correlation and acceptable rmse between estimated and inverse dynamics data.

The work is interesting and innovative. However, several aspects would benefit from modification /more detailed description or discussion.

Specific comments

The reviewer regrets the absence of page numbering (requested in the guide for authors).
>>> Page and line numbers are added accordingly.

The methodology section could provide more details about the 3PS. For instance, some technical specifications regarding the sensors are found much later in the discussion.
>>> The size and price of the sensors are moved to the methods (Page 6, Line 105-107).

The reviewer does not understand the link between the systematic review paper by Fong et al (2007) and the cloth sport shoes.
>>> The reference of the cloth sport shoe was incorrect. The correct one was missed. It was included in the revised manuscript.

The authors reference the review by Hertel (2002) to define the orientation of the axis of pronation-supination. The angles to the horizontal and sagittal plane mentioned here are those reported in by Inman (). In this respect, it seems useful to discuss (a) the way the perpendicular axes of the foot were determined in the present study, and (b) the issue of the individual variability of this axis (for instance Lundberg (1989) showed that the medial deviation of the axis averaged 18°, but with a standard deviation of over 16°), and its implication on the validity of their study.

>>> (a) The perpendicular orthogonal axes were determined with Vaughan et al's method (1992). The inversion/eversion axis was first defined as the vector from the virtual ankle coordinate to the toe tip. Secondary, by crossing the inversion/eversion axis of the foot segment to the medial-lateral axis of the shank segment, the internal/external rotation axis at the ankle joint was obtained. Finally, by crossing the internal/external rotation axis to the inversion/eversion axis, the plantarflexion/dorsiflexion axis at the ankle joint was obtained. We believe that the readers could refer to Vaughan's handbook for full reference, and thus we did not attempt to list all the details in the paper. (b) Discussion on the individual variability of the pronation-supination axis is added.

In the discussion, it would be useful to discuss the initial fluctuation/instable period, considering the aim of developing a "sprain-free sport shoe". In this respect, issues regarding reaction time, for instance, should be considered and the feasibility of the approach discussed.
>>> The estimated pattern followed the standard supination torque well, as it showed and in-phase fluctuation pattern. Such in-phase pattern indicated that the system could monitor the trend of changes without much delay. Moreover, the peak value of the estimation was about 95-105% of the standard data. All these suggested that the estimation was very good. This is revised in the first paragraph in Discussion: "The estimation could also show the instable period during the first 0.40s after landing in cutting motion, as indicated by an in-phase fluctuating pattern of ankle supination torque. The in-phase estimated pattern indicated that the system could monitor the trend of changes without much delay. For the magnitude of the peak value, the estimated values were about 95-105% in all motions."

Please use "calcaneus" instead of "calcaneous".
>>> Corrected accordingly.

The verb "to encounter" means "to meet" and not "to pool or put together".
>>> Corrected to "pooled together".

The term "real" is used at several instances in the manuscript to characterise the torque computed using inverse dynamics. This is an estimate, it may of course serve as a gold standard here, but confusion should be avoided.
>>> The term "real ankle supination torque" is revised to be "standard ankle supination torque".

In the discussion, the unit (probably seconds) of the instable period is missing.
>>> Corrected accordingly.

__Reviewer #2:__

This study developed a three-pressure-sensor (3PS) system for monitoring ankle supination torque during sport motions. Five male subjects wore a pair of cloth sport shoes and performed ten trials of walking, running, cutting, vertical jump-landing and stepping-down motions in a random sequence. A pair of pressure insoles (Novel Pedar model W, Germany) was inserted in the shoes for the measurement of plantar pressure at 100 Hz. The ankle joint torque was calculated by a standard lower extremity inverse dynamic calculation procedure with the data obtained by a motion capture system (VICON, USA) and a force plate (AMTI, USA), and was presented in a supination/pronation plane with an oblique axis of rotation at the ankle joint. Stepwise linear regression analysis suggested that pressure data at three locations beneath the foot were essential for reconstructing the ankle supination torque. Another group of five male subjects participated in a validation test with the same procedure, but with the pressure insoles replaced by the 3PS system. Estimated ankle supination torque was calculated from the equation developed by the regression analysis. Results suggested that the correlation between the real and estimated data was high (R = 0.938).

This is generally a good study but overall has insufficient data for a full paper. I think it is better suited as a technical note and should be shortened. There are few subjects (n=5) and no real question being tested.
>>> This paper is trimmed to be a Short Communication with 1500 words.

Other issues:

There is little description of the instrument.
>>> As the paper is further trimmed to a Short Communication, we could hardly describe the technical details of the instrument. However, we managed to describe the background principle and the method of calculation, and we are sure that reader could follow the method to fabricate their own similar system.

There are a number of grammatical and stylistic errors that need correction.
>>> We have checked again the grammar in the revised manuscript.

* Referee Suggestions

Referee suggestion

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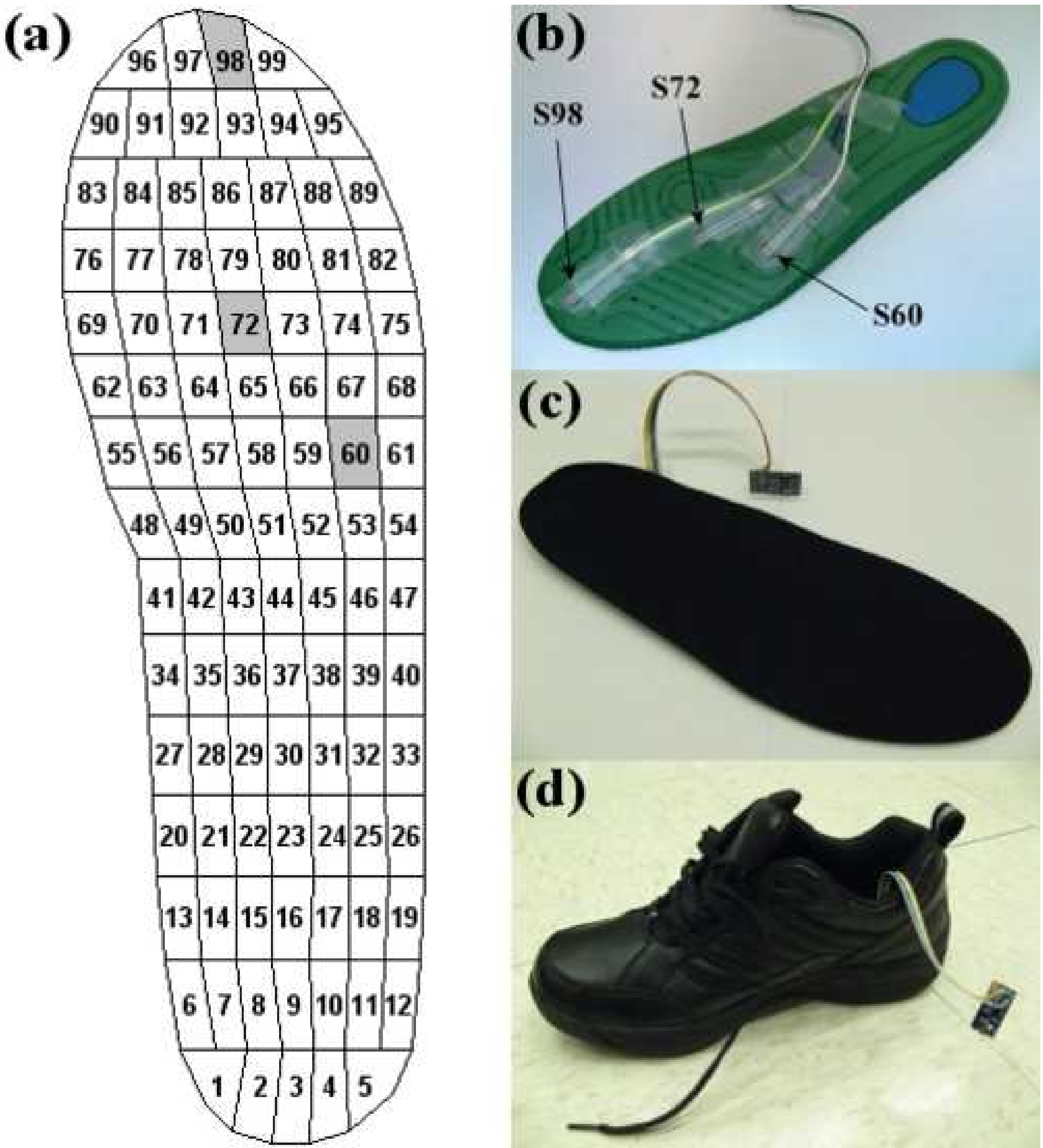
Figure legends

Figure 1 – (a) Location of the three pressure sensors (in right foot) required for the reconstruction of the ankle supination torque in the development test; (b) Three individual pressure sensors were attached to the required position beneath an insole; (c) The top side of the instrumented insole; (d) the sport shoe with the instrumented insole used in the validation test in this study.

Figure 2 – Relationship between the applied pressure (N/cm^2) and the output signal (unit-less, range = 0-1023) of the individual sensors in the instrumented insole with the numerical presentation.

Figure 3 – The pattern and the absolute error of the real (SupT) and estimated data ($SupT_{estimated}$) of one selected trial in each motion with an average accuracy among all trials.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Figure(2)
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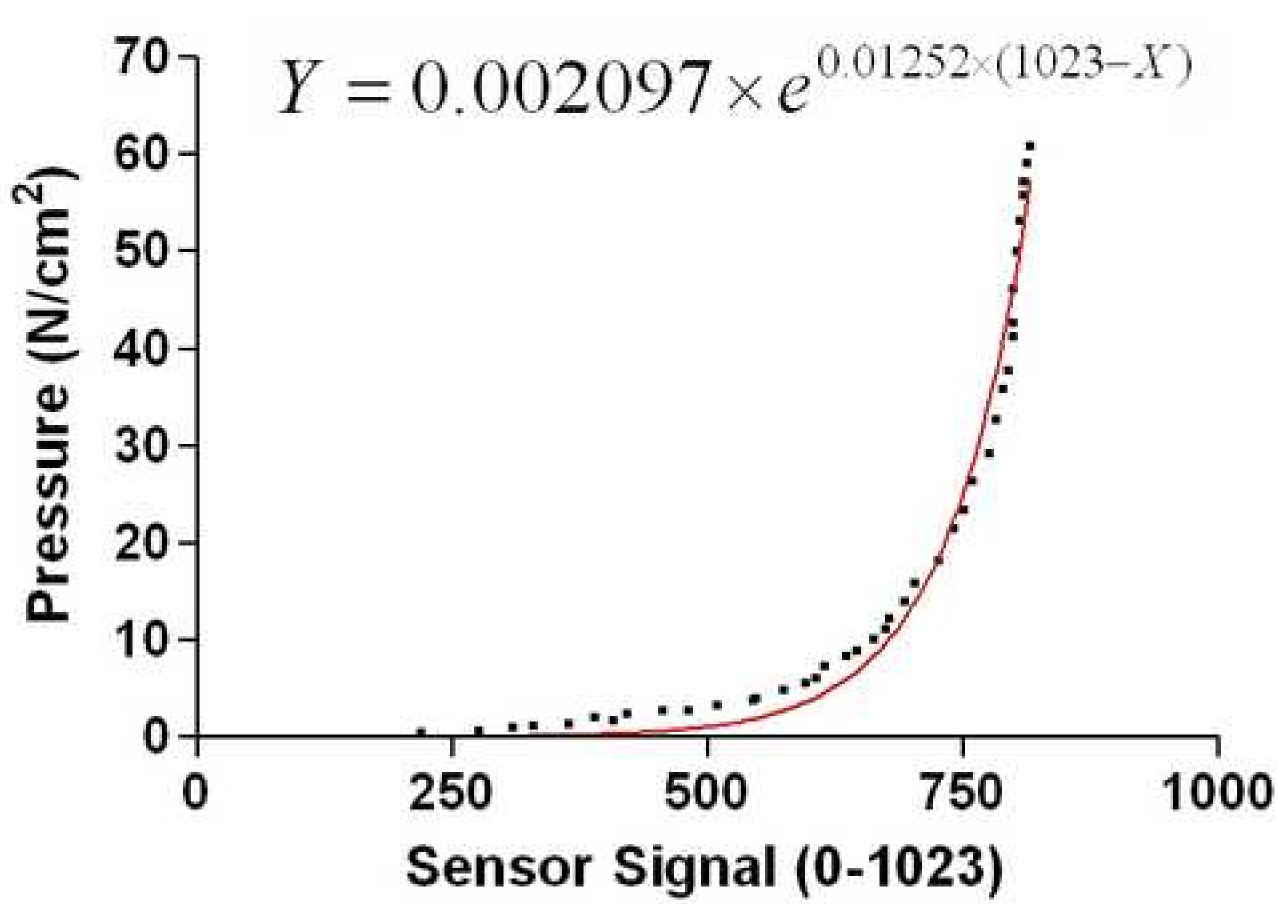

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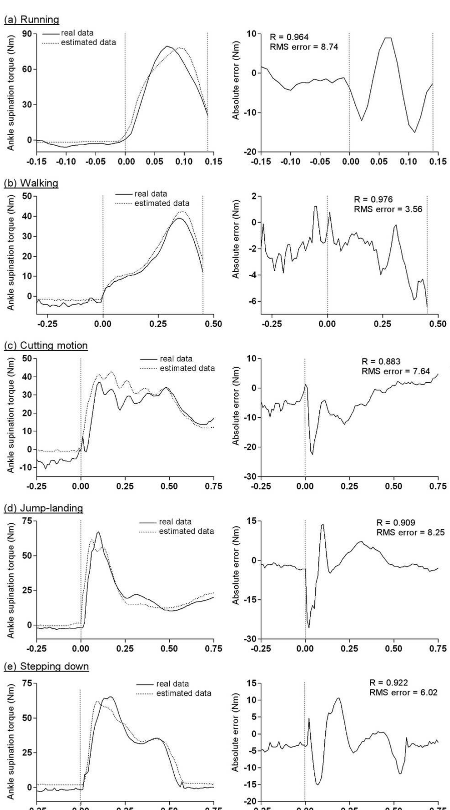

Table(s)

Table 1 – Accuracy of the ankle supination torque estimation as represented by the correlation (R) and the root mean square error (RMSE), and the peak torque value in all trials.

Motion	Subject 1		Subject 2		Subject 3		Subject 4		Subject 5		All subjects		Peak torque in all trials (Nm)
	R	RMSE	R	RMSE	R	RMSE	R	RMSE	R	RMSE	R	RMSE	
Running	0.980	3.95	0.983	5.77	0.980	6.99	0.980	7.87	0.947	10.42	0.961	8.78	113
Walking	0.990	1.94	0.993	1.70	0.988	2.35	0.980	3.42	0.972	4.27	0.978	3.29	51
Cutting	0.890	7.14	0.787	9.63	0.838	7.81	0.881	6.95	0.901	7.83	0.870	7.91	61
Jump-landing	0.903	7.57	0.914	6.37	0.909	6.75	0.920	5.61	0.898	9.67	0.899	8.16	104
Stepping-down	0.933	6.31	0.952	6.12	0.949	6.08	0.924	6.47	0.977	4.26	0.946	6.14	78
All	0.934	6.23	0.935	6.34	0.958	5.92	0.928	7.41	0.942	7.53	0.938	6.91	113