External Trunk and Limb Orientation Sensors for Human Movement

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Abstract

The purpose of this study was to verify the performance of recently developed body worn sensor packs versus 3-D motion analysis of trunk and lower-limb movements. Five sensor packs (Neopraxis Pty Ltd), each consisting of a microprocessor-controlled rate gyroscope and two 2-D accelerometers were attached to the trunk, thighs, and shanks of an able bodied subject. A 6 camera ExpertVision HiRES Motion Analysis System recorded multiple trials of sit-to-stand movements and normal walking. Time domain signals from each sensor pack were significantly correlated (r = 0.96 - 0.98; p<. 05) with the limb angle measurements calculated by the HiRES system. The cross-correlation function for the trunk, thigh and shank sensors with the HiRES data demonstrated values consistently greater than 0.90 without appreciable lag or phase shift. These data demonstrate that these external sensor packs are reliable and accurate devices for measuring trunk and lower-limb sagittal plane orientation in real-time.

Introduction/Background

Functional Electrical Stimulation (FES) systems have long been used to assist paraplegics with daily mobility tasks such as sit-to-stand transitions and gait. Artificial sensors have been a key element of these systems to provide the FES controller with feedback information about limb and trunk orientations. As such, the controller relies on accurate real-time information from the sensors to facilitate efficient and precise FES control.

Electrogoniometers, potentiometers, force sensing resistors, and event switches, have all been previously used in a laboratory setting but closed loop FES control has found little use in the clinical or home environments due to their cumbersome application and difficulties in donning or doffing.

Recent technological advancements in micro-machined electromechanical sensors have overcome the problems of size and mass, and many researchers are finding practical applications in FES control using accelerometers [1], gyroscopes [2], and a combination of these devices [3]. In fact, algorithms which fuse the information from accelerometers and gyroscopes have been shown to increase the accuracy of the estimate of the sensors orientation [4].

The purpose of this study was to evaluate recently developed body worn sensor packs against "gold standard" kinematic measurements from a 3-D optical motion analysis system (MAS).

Methods

An able-bodied subject completed multiple trials of sit-stand-sit transitions and normal walking in a biomechanics laboratory outfitted with a 3-D motion analysis system (HiRES). Each trial lasted approximately 10 seconds whereby the subject performed each task at a normal self-selected pace.

SENSOR PACKS

Each sensor pack consisted of two 2-D accelerometers (Analog Devices ADLX202), a rate gyroscope (Murata ENC03J), a micro-controller (Atmel ATMega103L) and signal conditioning electronics. Each pack measured 75x50x25mm in size and derived its power from an external controller.

LABORATORY SETUP

A sensor pack was fitted to each thigh, shank and trunk of the subject. Queued Serial Peripheral Interface cables relayed commands to the sensor packs from the controller and collected real-time kinematic data from each pack. Additionally, retro reflective balls were aligned on bony landmarks of the subject to identify corresponding limb segments.

Six high-speed infrared cameras (Falcon), sampling at a rate of 60 frames per second, were used to capture the movement of the subject. To synchronise data collection between the sensors and the MAS a signal from the controller was collected by an analogue channel of the MAS at the start of each trial.

Data from the MAS were later analysed with a biomechanical software package (Kintrak) to produce 3-D angular information of the lower limb segments and trunk. Statistical analyses comprised cross-correlation and root mean square error (RMSE) calculations between the sensor packs and the MAS data using SPSS for Windows.

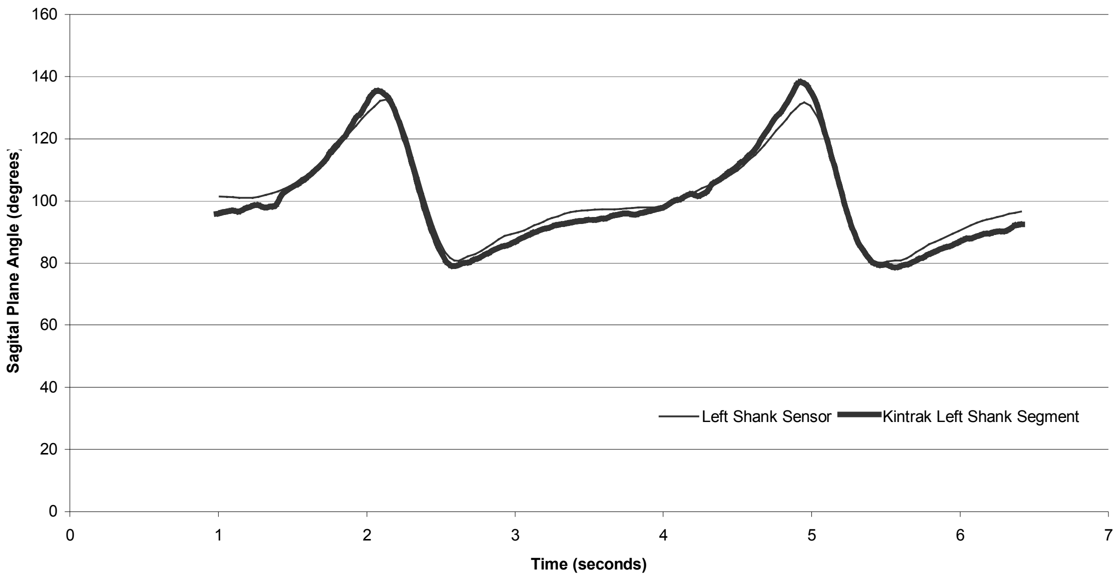


Figure 1. Sagittal plane angle of the left shank recorded by the MAS and a sensor pack during a walking trial. The sensor pack begins recording approx. 1 second after the trial begins.

Table 1. Root mean square error (RMSE) and cross correlation between the MAS and sensor pack sagittal plane angle during a walking trial.

Body Segment	**RMSE**	**Cross-correlation**
Trunk	1.45°	0.970
Left Thigh	4.24°	0.971
Right Thigh	2.92°	0.988
Left Shank	2.97°	0.991
Right Shank	3.00°	0.900

Results

Orientation data of each thigh, shank and the trunk were stored on the controller for later comparison to the MAS data of limb orientation. Figure 1 displays an example of the two orientation techniques during a walking trial. The Kintrak and sensor data were interpolated to a common sampling frequency and statistically treated (Table 1) to calculate RMSE and cross-correlation. The cross-correlation between sensor and MAS data were uniformly high with R^2 of 81% - 98% without appreciable lag or phase shift.

Discussion/Conclusions

These data suggest that body worn external sensor packs are reliable and accurate devices for measuring trunk and lower-limb sagittal plane orientation in real-time.

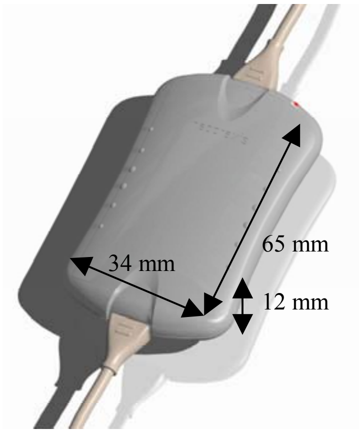
The results obtained by our sensors are in good agreement with those reported by other research groups. Tong and Granat [2] measured RMSE of gyroscope sensors versus a MAS and calculated values of approximately 5°.

As such, their eventual use for closed-loop feedback control of both skin surface and implanted FES systems represents a promising approach for lower limb neuroprothesis that aim to enhance functional mobility in paraplegia.

Future Research and Development

Newer packaging of the sensor packs has resulted in a reduction of size by approximately 72%(Figure 2).
This reduction in size is important, since in our current study the larger size of sensor pack occasionally shifted on a limb during movement. Interestingly findings by Houdayer et al. (unpublished) have demonstrated that the placement of sensors on the limb was not critical

Figure 2. Repackaged sensor pack



for the accurate measurement of sagittal plane orientation of that segment. However if these sensors are to be deployed in "mission critical" closed loop control of FES assisted functional mobility, future research needs to identify whether sensor pack movement during gait presents inaccuracies for both the sagittal and coronal plane limb orientations.

In conclusion, this study demonstrated that external sensor packs are reliable and accurate devices for measuring trunk and lower-limb sagittal plane orientation in real-time. Comparison of sensor pack sagittal plane data with kinematic measurements from a 3-D optical motion analysis system yielded cross-correlations in the range of 0.90 – 0.99 with low RMSE. Further research is warranted to determine if these sensor packs can be deployed in closed-loop FES control of functional mobility where real-time resolution of both sagittal and coronal plane limb orientations may be required.

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