Knee Joint Angles and Spatio-Temporal Parameters Estimated via Wearable Inertial Sensors

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Introduction

Gait analysis in medical practice is mostly done by camera-based motion analysis systems, which provide good results but presents serious drawbacks (costs, complexity). Thus, small-size low-cost wireless inertial sensors are an emerging tool for monitoring gait. Aim of the work is to implement a wireless inertial system, with 2 sensors (on thigh and shank), for evaluating joint angles plus spatio-temporal variables for several test. Results are promising and demonstrate the goodness of the realized system.

Methods

Knee flexion/extension angles are calculated as follows:

1. Thigh/shank sensor frames aligned vertically/horizontally;
2. Orientation estimation;
3. Differential orientation, conversion into angle-axis representation, and joint angle extrapolation.

As per spatio-temporal parameters:

- Temporal events (toe-offs, heel-strikes, etc...) estimated from shin's gyro.
- Stride time (ST) estimated by measuring the time between two toe-offs.
- Stride length (SL) calculated with 2 approaches: geometrically with a human gait model (1st method), or directly integrating inertial signals (2nd one).
- Stride speed (SS) calculated by dividing SL and ST.

Results

The system consists of 2 Tyndall Wireless Inertial Measurement Units (WIMUs) with 3D accelerometer/gyro (250 Hz) and WiFi. Algorithms are implemented in Matlab, and the test considered are walking, drop and Sit-to-Stand. As for spatio-temporal feature (Table I), SL/SS are similar with both methods, though the second one presents smaller mean errors but higher variability. Knee joint angles are validated (Fig. 1) with a high-speed camera. Results (Table I) show good repeatability and accuracy for all test (i.e. 3.9 deg for walking). Pearson's r is between 0.97-0.99.

Conclusions

This work presents a wearable inertial system for the implementation of a complete gait analysis for a wide set of test. Overall results present good repeatability and the accuracy is comparable with the state-of-the-art.

Table I: Results

Spatio-Temporal Parameters			
Actual SS (m/s)	0.97	1.11	1.66
ST (sec)	1.19 ± 0.03	1.07 ± 0.01	0.91 ± 0.01
SL (m) – first method	1.02 ± 0.02	1.03 ± 0.02	1.48 ± 0.025
SL (m) – second method	1.05 ± 0.11	1.04 ± 0.11	1.53 ± 0.15
SS (m/s) – first method	0.87 ± 0.02	0.96 ± 0.02	1.62 ± 0.025
SS (m/s) – second method	0.9 ± 0.1	0.96 ± 0.07	1.67 ± 0.16
Knee Joint Angles			
	Mean error ± st_dev (deg)	**Pearson's r**	**RMSE (deg)**
Walking (0.97 m/s)	2.28 ± 2.2	0.992	3.16
Walking (1.11 m/s)	-0.89 ± 3.91	0.978	4.01
Walking (1.66 m/s)	-1.85 ± 4.18	0.969	4.56
Drop Test	4.92 ± 7.11	0.968	9.6
STS Test	5.41 ± 5.65	0.972	7.81

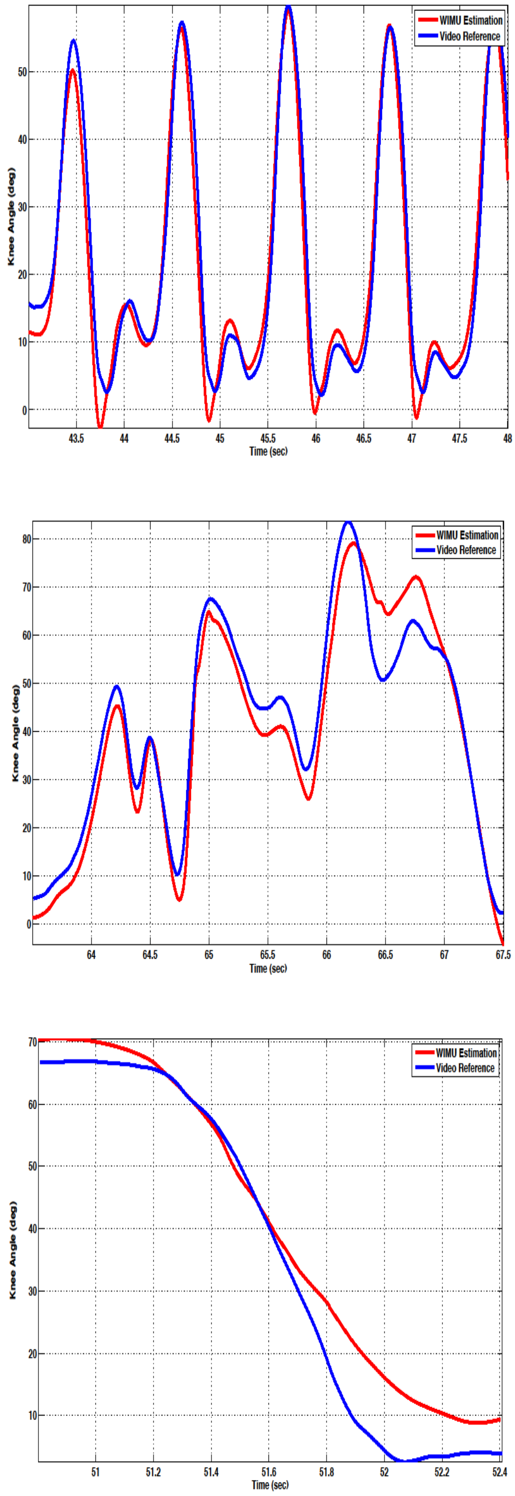

Fig. 1. Knee angles from WIMUs (red line) and camera (blue) for one subject performing walking test at 1.11 m/s (top), drop test (centre) and STS test (bottom).