Wearable Inertial Sensors as a Tool for Quantitative Assessment of Progress during Rehabilitation

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***Abstract*— Biomechanics analysis is frequently used in both clinical and sporting practice in order to assess human motion and performance of defined tasks. Whilst camera-based motion systems have long been regarded as the 'Gold-standard' for quantitative movement-based analysis, their application is not without limitations as regards potential sources of variability in measurements, high costs, and practicality of use for larger patient/subject groups. Another more practical approach, which presents itself as a viable solution to biomechanical motion capture and monitoring in sporting and patient groups, is through the use of small-size low-cost wearable Micro-ElectroMechanical Systems (MEMs)-based inertial sensors. The clinical aim of the present work is to evaluate gait during rehabilitation following knee injuries and to identify gait abnormalities through a wireless inertial sensing system. This system was developed at the Tyndall National Institute to meet clinician-defined needs, and is able to provide a complete biomechanics assessment without the constraints of a motion capture laboratory. The derived motion parameter outcomes can be analyzed by clinicians and sport scientists to study the overall patients' condition and provide accurate medical feedback as to their rehabilitative progress. Detection of atypical movement characteristics is possible by comparing the performance and variability in motion characteristics in the patient's affected and unaffected lower-limbs. The work is ongoing, and to date the system has been tested on only one impaired subject, additional clinical trials are currently being planned with an enhanced number of injured subjects. This will provide a more robust statistical analysis of the data in the study. The present feasibility study proved that inertial sensors can be used for a quantitative assessment of knee joint mobility, and gait mechanics during the rehabilitation program of injured subjects and can provide valuable information to clinical experts as regards patient rehabilitation.**

Keywords- Inertial Sensors; Wearable Microsystems; Rehabilitation.

I. INTRODUCTION

Biomechanics analysis is frequently used in both clinical and sporting practice by clinicians to track patient progress and to define rehabilitations programs through the assessment of human motion during the performance of defined tasks. Common examples include the use of camera-based motion analysis systems during formal gait analysis by rehabilitation professionals to ascertain measurements of Temporal (Time) & Spatial Characteristics associated with gait parameters. This enables clinicians to identify gait deviations in paediatric and amputee populations, screening elderly people for risk of falling, to objectively monitor patient's progress, and to help determine the efficacy of surgical and therapy interventions [1]-[4].

Whilst camera-based motion systems have long been regarded as the 'Gold-standard' of quantitative movement-based analysis, their application is not without limitations as regards potential sources of variability in measurements, relatively high costs of instrumentation including access to specialist motion labs, as well as practically of application for larger patient/subject groups, as has been discussed by Chau et al. [5].

From a clinical perspective, observational forms of clinical gait analysis frequently forms the corner stone of patient knee joint assessment, and is typically used in parallel with manual clinical assessment techniques, such as stress-testing evaluation of joint laxity, range of movement (ROM), and manual and/or isokinetic strength assessment, as well as contextual subjective patient questionnaires, such as International Knee Documentation Committee (Form) IKDC [1][3].

However, the use of observational gait analysis (non-empirical assessments), even when used by experienced clinicians, may not be adequate or sensitive enough to detect subtle clinical pathological changes in movement following knee surgery [3][4].

Another approach, which has been explored as a more practical and viable solution to biomechanical motion capture and monitoring in sporting and patient groups, is through the use of small-size low-cost wearable inertial sensors [1][3][4].

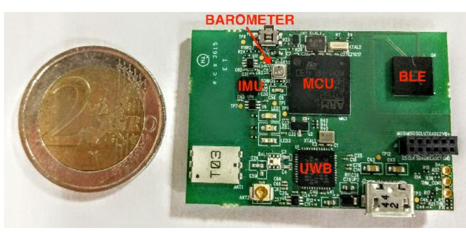

Figure 1. Tyndall Wireless Inertial Measurement Unit (WIMU)

Nevertheless, despite the great amount of work presented in literature on inertial sensors for biomechanics, such a technology has been adopted for monitoring lower-limbs during rehabilitation or tele-rehabilitation only in few cases (for example [6][7]). In even fewer cases, inertial sensors were adopted to assess injured athletes' joint movement during rehab (such as, ankle [8] or shoulder [9]). To the best of authors' knowledge, only one study [10] has investigated athletes' movement following knee injuries; however, the proposed solution (e.g., a full-body suit equipped with 10 wearable sensors) may be cumbersome.

The clinical aim of the present ongoing work is to evaluate gait during rehabilitation following knee injuries and to identify gait abnormalities through a wireless portable easy-to-use inertial sensing system. The wireless sensing system, developed at the Tyndall National Institute, consists of two sensors per limb, and is able to provide a complete biomechanics assessment (without the constraints of a laboratory) for a series of scripted activities. The derived outcome can be analyzed by clinicians and sport scientists to study the overall patients' condition and provide accurate medical feedback, thus proving that inertial sensors can be used for a quantitative assessment of knee joint mobility, and gait mechanics during the rehabilitation program of injured athletes.

This work was a phase one feasibility study. In order to further validate the drawn conclusions in statistical terms, additional clinical trials, with larger and homogeneous populations, are needed and currently being planned. This feasibility study represent a prerequisite to a larger cross-sectional/cohort trial that will assess sport performance analysis and movement pattern alterations detection in people following knee injuries pathologies through wearable inertial sensing technology. Ethics approval has been secured for this proof-of-concept work and larger scale validation trials.

The present work is organized as follows. The methodology of the study, with a description of the hardware and of the protocol used during the test, are described in Section II. The obtained results are shown in Section III and exhaustively analyzed and discussed, also providing new requirements for future clinical trials. Finally, conclusions are drawn in the last section.

II. Methodology, Hardware, and Protocol

The parameters taken into account for a complete assessment are as follows:

- Temporal events: toe-offs, heel-strikes, mid-stance;
- Temporal intervals: gait cycle duration, stance phase, swing phase, single and double support, cadence (or step rate), number of cycles, swing symmetry;
- Spatial parameters: stride length, stride velocity (or speed), peak angular velocity, shank clearance;
- Knee range of motion.

For each of those parameters, it is possible to calculate min, max, mean, median, standard deviation values and extrapolate the related Coefficient of Variability (CV).

The system consists of two Tyndall Wireless Inertial Measurement Units (WIMUs) per leg with 3D accelerometer/gyro (@ 400 Hz) and Bluetooth Low-Energy/SD cards (Fig. 1). WIMUs have been attached to the anterior tibia, 10 cm below the tibial tuberosity, and to the lateral thigh, 15 cm above the tibial tuberosity using surgical adhesive tape.

The data fusion algorithms are implemented in Matlab, and the scenarios considered are walking and hamstring curl – defined by physiotherapists as good indicators of rehabilitation progress. In the walking scenario, the subject stands on a treadmill, which is then being operated at different speeds (3 and 4 km/h) for approximately one minute per test. In the hamstring curl scenario, the subject stands and bends the knee raising the heel toward the ceiling as far as possible without pain, relaxing the leg after each repetition. A significant number of repetitions for each scenario was carried out, so as to provide an accurate picture of the conditions. The system has been tested with an impaired subject. The impaired subject is a female athlete, age: 44, height: 161 cm, and weight: 52 kg, with good general health status, with history of knee injuries in the last 2 months before testing (reconstructed anterior cruciate ligament in the left leg following a sporting injury), and tested for 3 months starting from one month after surgery.

III. Results and Discussion

Knee joint angles have been estimated for the participant. Results are shown for the hamstring curl scenario in Fig. 2 (left leg on the left, and right leg on the right), where each line indicates the reference joint angle values extrapolated from the exercises performed by the unimpaired subject at 4, 6, 8, and 10 weeks following the knee surgery. Those lines represent the average characteristic of all the individual repetitions carried out at each testing session. While the lines for the right lower-limb are always consistent throughout the rehabilitation process, the left impaired lower-limb shows a great difference in the results obtained in the first session (after 4 weeks) compared to the other ones. All the following sessions are comparable also for the left lower-limb.

Finally, all the gait spatio-temporal parameters mentioned in Section 2 have been calculated for the walking scenario (at 3 and 4 km/h) for both legs of the impaired subject. Results are summarized in Fig. 3.

As per the temporal variables, the first session after 4 weeks shows a strong difference between left and right leg due to injury's effects on gait, especially highlighted by the CV. In the following testing sessions, performance from affected and unaffected lower-limbs become comparable. Those considerations are valid for both speeds of the walking scenario.

Dissimilarities are also clear as per spatial parameters.

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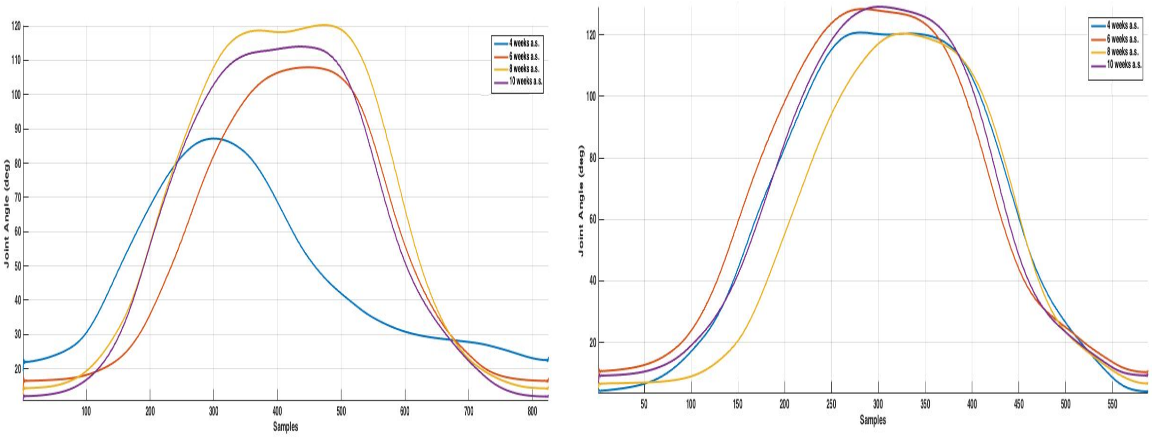

Figure 2. Joint Angles for left leg (left) and right leg (right) measured throughout rehabilitation (hamstring curl exercise).

	4 weeks a.s.		6 weeks a.s.		8 weeks a.s.		10 weeks a.s.	
	Left Leg	Right Leg	Left Leg	Right Leg	Left Leg	Right Leg	Left Leg	Right Leg
Gait Cycle Duration (s)	1.3264 ± 0.0540 (4.0707)	1.3275 ± 0.0188 (1.4184)	1.4049 ± 0.0166 (1.1806)	1.4030 ± 0.0179 (1.2766)	1.4053 ± 0.0196 (1.3976)	1.4092 ± 0.0198 (1.4031)	1.3572 ± 0.0224 (1.6472)	1.3587 ± 0.0194 (1.4310)
Stance Phase (s)	0.8535 ± 0.0471 (5.5159)	0.8560 ± 0.0144 (1.6859)	0.8828 ± 0.0130 (1.4753)	0.9121 ± 0.0153 (1.6726)	0.8942 ± 0.0204 (2.2778)	0.9171 ± 0.0138 (1.5095)	0.8541 ± 0.0224 (2.6248)	0.8957 ± 0.0173 (1.9320)
Swing Phase (s)	0.4730 ± 0.0489 (10.3425)	0.4715 ± 0.0101 (2.1442)	0.5221 ± 0.0124 (2.3671)	0.4908 ± 0.0109 (2.2123)	0.5111 ± 0.0071 (1.3962)	0.4922 ± 0.0128 (2.6004)	0.5031 ± 0.0152 (3.0247)	0.4630 ± 0.0087 (1.8799)
Single Support (s)	0.9444 ± 0.0523 (5.5378)		1.0129 ± 0.0168 (1.6558)		1.0032 ± 0.0130 (1.2921)		0.9662 ± 0.0191 (1.9744)	
Double Support (s)	0.3830 ± 0.0511 (13.3479)		0.3920 ± 0.0144 (3.6648)		0.4060 ± 0.0152 (3.7526)		0.3926 ± 0.0230 (5.8471)	
Cadence (step/min)	45.2346	45.1977	42.7082	42.7656	42.6959	42.5762	44.2072	44.1590
Swing Simmetry	1.0076 ± 0.1056 (10.4839)		0.9406 ± 0.0293 (3.1191)		0.9633 ± 0.0313 (3.2443)		0.9210 ± 0.0278 (3.0197)	
Stride Length (m)	0.9218 ± 0.1436 (15.5630)	1.2633 ± 0.0717 (5.6783)	1.0038 ± 0.0693 (6.9074)	1.0881 ± 0.0744 (6.8416)	0.9514 ± 0.0614 (6.4526)	1.1749 ± 0.0960 (8.1704)	1.0061 ± 0.0932 (9.2608)	1.0271 ± 0.0670 (6.5214)
Stride Speed (m/s)	0.6953 ± 0.1067 (15.3439)	0.9517 ± 0.0541 (5.6878)	0.7144 ± 0.0474 (6.6413)	0.7754 ± 0.0492 (6.3493)	0.6770 ± 0.0421 (6.2134)	0.8335 ± 0.0651 (7.8095)	0.7410 ± 0.0643 (8.6810)	0.7560 ± 0.0488 (6.4557)
Shank Clearance (m)	0.0242 ± 0.0049 (20.2683)	0.0645 ± 0.0126 (19.6077)	0.0217 ± 0.0050 (23.1823)	0.0346 ± 0.0070 (20.3285)	0.0175 ± 0.0035 (19.8007)	0.0285 ± 0.0081 (28.5536)	0.0404 ± 0.0077 (19.1704)	0.0343 ± 0.0065 (19.0170)

	4 weeks a.s.		6 weeks a.s.		8 weeks a.s.		10 weeks a.s.	
	Left Leg	Right Leg	Left Leg	Right Leg	Left Leg	Right Leg	Left Leg	Right Leg
Gait Cycle Duration (s)	1.1782 ± 0.0760 (6.4469)	1.1874 ± 0.0169 (1.4195)	1.2156 ± 0.0158 (1.3031)	1.2156 ± 0.0177 (1.4587)	1.1579 ± 0.0305 (2.6329)	1.1552 ± 0.0134 (1.1590)	1.1556 ± 0.0146 (1.2609)	1.1532 ± 0.0169 (1.4726)
Stance Phase (s)	0.7734 ± 0.0532 (6.8757)	0.7369 ± 0.0140 (1.9010)	0.7647 ± 0.0155 (1.8014)	0.7438 ± 0.0134 (2.0329)	0.7070 ± 0.0206 (2.9096)	0.7217 ± 0.0116 (1.6060)	0.7092 ± 0.0128 (1.8086)	0.7254 ± 0.0125 (1.7251)
Swing Phase (s)	0.4048 ± 0.0613 (15.1344)	0.4504 ± 0.0096 (2.1377)	0.4719 ± 0.0060 (1.2652)	0.4509 ± 0.0096 (2.1247)	0.4509 ± 0.0201 (4.4652)	0.4335 ± 0.0088 (2.0206)	0.4464 ± 0.0063 (1.4001)	0.4278 ± 0.0093 (2.1727)
Single Support (s)	0.8552 ± 0.0609 (7.1259)		0.9228 ± 0.0115 (1.2477)		0.8844 ± 0.0243 (2.7436)		0.8742 ± 0.0120 (1.3770)	
Double Support (s)	0.3230 ± 0.0518 (16.0521)		0.2928 ± 0.0159 (5.4296)		0.2735 ± 0.0221 (8.0865)		0.2813 ± 0.0107 (3.8179)	
Cadence (step/min)	50.9261	50.5320	49.3577	49.3573	51.8167	51.9397	51.9220	52.0280
Swing Simmetry	1.1414 ± 0.1928 (16.8902)		0.9560 ± 0.0231 (2.4184)		0.9627 ± 0.0373 (3.8788)		0.9586 ± 0.0229 (2.3890)	
Stride Length (m)	1.0786 ± 0.0893 (8.2798)	1.3574 ± 0.0484 (3.5631)	1.0620 ± 0.0450 (4.2325)	1.2122 ± 0.0828 (6.8283)	0.9792 ± 0.1695 (17.3061)	1.2087 ± 0.0406 (3.3598)	1.1661 ± 0.0495 (4.2479)	1.1794 ± 0.0851 (7.2171)
Stride Speed (m/s)	0.9175 ± 0.0778 (8.4793)	1.1431 ± 0.0368 (3.2216)	0.8738 ± 0.0393 (4.5020)	0.9974 ± 0.0710 (7.1193)	0.8457 ± 0.1467 (17.3504)	1.0463 ± 0.0333 (3.1800)	1.0090 ± 0.0376 (3.7263)	1.0224 ± 0.0673 (6.5763)
Shank Clearance (m)	0.0277 ± 0.0051 (18.3936)	0.0553 ± 0.0080 (14.4414)	0.0255 ± 0.0033 (13.0101)	0.0502 ± 0.0132 (26.3869)	0.0281 ± 0.0053 (18.9419)	0.0499 ± 0.0144 (28.8038)	0.0411 ± 0.0052 (12.5986)	0.0469 ± 0.0079 (16.8087)

Figure 3. Walking spatio-temporal parameters at 3 (up) and 4 (down) km/h for each testing session. Mean and St. Dev. shown. CV is indicated in brackets

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For instance, the evident difference (roughly 30 cm) between left and right stride length in the injured subject at 3 and 4 km/h in the first session is much larger compared to the same divergence measured during the remaining testing sessions. Indeed, the left stride length for the impaired athlete is always shorter compared to her right stride length at every speed and for every session.

The CV associated to the stride length is an additional parameter that further shows this dissimilarity. The average CV for the right stride length is always consistent at each session, whilst this is not evident in the CV measured on the subject's left lower-limb, especially on the session after 4 weeks.

The same characteristics are observed in the estimation of stride speeds and shank clearance. The difference between left and right stride speed in the following sessions is much limited compared to the same variable measured during the first one. The associated CV for right and left stride speed proves this conclusion as well.

Finally, while the difference between the mean values of left and right shank clearance is consistent at the first session at 3 km/h, and is limited in the following weeks, such a difference remain visible until the 4th session (after 10 weeks) when considering the speed at 4 km/h, which involves higher dynamic movements.

All those results indicate that the gait measurements gathered from the subject after 6 weeks are far more repeatable and stable than the gait variables collected at the first session. Therefore, this feasibility study has proved that the studied wearable inertial sensing technology is able to potentially detect atypical gait movement characteristics accurately and reliably by comparing performance and differences in the affected and unaffected lower-limbs.

Those results also proved how critical and important the first 6 weeks of rehabilitation after knee surgery may be, which should be targeted and analyzed with much frequent data captures in the following studies. Moreover, it has been shown how only joint angles or gait spatio-temporal parameters may be too limited in order to provide a complete picture of the subject's condition after the first phase of rehabilitation. Therefore, new variables should be considered so as to define also more subtle aspects of the gait change, such as postural sway, the energy expenditure and the movements' smoothness.

Finally, given that alongside re-education of motor patterning, muscular reconditioning is an important rehabilitation goal during the restoration of function after injury, further exercises targeting fatigue and muscle strength/power estimation should be included into the protocol for the following studies, so as to have a better understanding of the overall patient's progress throughout the procedure.

IV. CONCLUSIONS & FUTURE WORK

This work presented a wearable inertial system for an objective assessment of lower-limbs. Detection of atypical movement characteristics was measured by comparing performance and differences in the affected and unaffected lower-limb. The test subject will continue to be monitored throughout the complete rehabilitation in order to measure her response to therapeutic treatment. An enhanced number of subjects, with homogeneous characteristics, will also be tested in the future so as to have a more robust base for the study and further validate the drawn conclusions in statistical terms. These additional clinical trials are under development.

However, the present feasibility study proved that inertial sensors can be used for a quantitative assessment of knee joint mobility, and gait mechanics during the rehabilitation program of injured subjects.

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