Application of inertial sensors in rehabilitation robotics

E. Rocon, J.C. Moreno, A.F. Ruiz, F. Brunetti, J.A. Miranda, J.L. Pons

Abstract— **MicroElectroMechanical Systems (MEMS) are revolutionizing a multitude of industries world wide, from consumer products to the scientific community. Rehabilitation robotics is a robotic field specially interested in using the advantages of inertial sensors. The essential aspect in this area is the intrinsic interaction between human and robot, which imposes several restrictions in the design of this sort of robots. This paper addresses the analysis of the application of inertial sensors as sensing technologies in controlled orthotic devices with a detailed analysis with two biomechatronic robotics rehabilitation exoskeletons, one for the upper and other for the lower limb. Eventually, the results and conclusion of the experiments are given.**

Index Terms— **inertial sensing, orthotics, rehabilitation robotics, MEMS.**

I. Introduction

MicroElectroMechanical Systems (MEMS) are revolutionizing a multitude of industries world wide, from consumer products to the scientific community. Motion sensing, by means of MEMS inertial sensors, could be applied to a wide array of consumer products - laptops computers, cell phones, PDAs, camcoders, digital cameras, gaming, computer input devices and pagers. Another enormous field which is using inertial sensors are the automotive application. Safety, passenger comfort, vehicle performance and navigation are triggering new and tremendorous demand for inertial sensors.

In addition, these sensors represented a real scientific breakthrough in the medical field, where there is a need for small ambulatory sensor systems for measuring the kinematics of body segments. Inertial sensors would enable ambulatory biomechanical measurements. Since micromachined sensors such as gyroscopes and accelerometers have become generally available, human movement can be measured continuously outside a specialized laboratory with ambulatory systems.

Lately, the application of this technology in robotics field is increasing very fast, mainly in robot navigation which requires six-degrees-of-freedom motion estimation, both acceleration and angular rate about three axes. The greater the ability to sense the full motion of the robot and its parts, the better the control over its behavior. This technology is being used together with others sensors applied in robot navigation, for instance cameras, since each can be used to resolve the ambiguities in estimated motion that result from using the other modality alone. For instance, image measurements can counteract the error that accumulates when integrating inertial readings, and can be used to distinguish between the effects of sensor orientation, acceleration, gravity, and bias in accelerometer measurements. On the other hand, inertial data can resolve the ambiguities in motion estimated by a camera that sees a degenerate scene, such as one containing too few features, features infinitely far away, or features in an accidental geometric configuration; to remove the discontinuities in estimated motion that can result from features entering or leaving the camera's field of view; to establish the global scale; and to make motion estimation more robust to mistracked image features [1].

Another area of robotics which is specially interested in using the advantages of inertial sensors is the rehabilitation robotics field. The scientific community is becoming more and more interested in the so-called Rehabilitation Robotics. Rehabilitation robots are robots intended to restore or replace some human function. Over the last decade, the introduction of robotic technologies into rehabilitation settings has progressed from concept to reality. Numerous studies have demonstrated the efficacy and advantages of rehabilitation robots for assessing and treating motor impairments in both the upper and lower extremities [2]–[5].

The essential aspect in this area is the intrinsic interaction between human and robot. This interaction has a twofold scenario: first, a cognitive interaction that allows the human to control the robot while it feeds information back to the human; second, a biomechanical interaction leading to the application of controlled forces between both actors. Both factors influence the different components of the system such as the sensors of the robot.

In this sort of application, there is a need to obtain variables such as joint angular accelerations and angular velocities to close control loops chasing specific goals. In addition, the sensor should have specific characteristics such as low size with long battery life, should be able to extract a wide range of parameters from human motion, easy adaptability to an orthotic frame, proper bandwidth and other preferred features. These characteristic made MEMS inertial sensors very attractive for rehabilitation robotics field. Despite the increase number of applications employing inertial sensor, rehabilitation robots are still not exploring all the benefits of this technology.

Rehabilitation robotics applications requires the analysis of the body motion in order to close control loops around defined joints. Nowadays, there are many systems for measuring body segment position and angles between segments. Commercial optical systems such as Vicon, [6], are considered the standard in human motion analysis. Although

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this system provides accurate position information, there are some significant limitations such as high costs and limited measure volume. They have to be used in laboratories with a fixed equipment, which impedes its use in rehabilitation robotics applications, like exoskeletons. This has promoted the use of inertial sensors in rehabilitation robotics field.

Inertial sensors give an output signal proportional to its own motion respect to an inertial frame of reference, allowing the fabrication of motion sensors "internally referenced". The vestibular system, located in the inner ear, is a biological 3D inertial sensor. It can sense angular motion as well as linear acceleration of the head. Micromachining techniques make possible the development of precision inertial sensors with a lower price and standard characteristics similar to those of integrated circuits, suitable for portable and wearable applications.

Miniature sensor units are placed on each body segment to be analyzed. A rate gyroscope measures angular velocity relying on the Coriolis force principle during angular rate by measuring capacitance. An accelerometer measures acceleration governed by a physical principal known as Hookes law. Noise and bias errors associate with small sensors make it unpractical to track orientation and position changes for long time periods if no compensation is applied [7].

Combinations of three axial gyroscopes and accelerometers, have been proposed to obtain complete kinematics of single sensor units, [8], [9]. Application in robotic navigation systems has been broadly investigated, combined with other wide scale positioning techniques (i.e., GPS). But applications in robotics concerning measurement and control of human motion commonly require a method to obtain segments orientation. Integration of angular velocity given by a gyroscope can be used as a method to estimate orientation, if compensation methods to correct the resultant integration drift are used, which is mainly caused by fluctuation of the sensor offset. Such compensation in free motion applications, can be performed using inclination data from three axial accelerometers, together with a priori knowledge of a particular movement, such as constraints imposed by joints, as described by Luinge, [10], for the upper arm. Also, when rhythmic movements are involved (i.e., walking, tremor), cyclical compensatory mechanisms can be applied to accurately obtain orientations or to obtain quantities of interest to fed a given controller of motion, as will be presented in this paper.

Despite the massive use of inertial sensors a a tool to analyze motion in robotic applications, few are used for closing control loops. The robotics devices presented in this paper successfully use their sensors in order to close specific control loops. This paper addresses the analysis of inertial sensors as sensing technologies in controlled orthotic devices. It aims at illustrating the successful use of this particular technology in two rehabilitation robots recently developed. In both applications, in addition to measure human motion, these sensors were successfully used for closing specific control loops, without affecting the stability of the devices. The analysis will be complemented by the description of experimental results of inertial sensors that demonstrates its application on wearable robotic systems. In the next section, the main principles for movement analysis based on inertial sensors are described. In section III and IV, experiments with two biomechatronic robotics rehabilitation exoskeletons for the upper and lower limb will be shown. Eventually, some discussion on the conclusions and future work are given.

Fig. 1. WOTAS exoskeleton for tremor suppression.

II. On the Use of Rate Gyroscopes for Tremor Sensing in the Human Upper Limb

WOTAS (Wearable Orthosis for Tremor Assessment and Suppression) is an active upper limb exoskeleton based on robotics technologies capable of applying forces to cancel tremor and retrieve kinematic information from the tremorous upper limb, [4]. WOTAS follows the kinematics structure of the human upper limb and spans the elbow and wrist joints. It exhibits three degrees of freedom corresponding to elbow flexo-extension, forearm pronation-supination and wrist flexo extension, see figure 1. In order to monitor and suppress tremor, the WOTAS exoskeleton is equipped with kinematic (angular position, velocity and acceleration) and kinetic (interaction force between limb and exoskeleton) sensors. Tremor force, position, velocity and acceleration are the required information to implement control strategies.

MEMS Gyroscopes were chosen because they can measure rotation movements and human movement can be described as rotational about joints [11], [12]. The element sensor selected was the uniaxial gyroscopes sensor developed by Technaid S.L. (www.technaid.com), their dimensions were 15,5x8x4 mm and its weight was 20 grams, which is a low-mass system when compared to other sensors used in the field, [12]. Technaid offers a broad range of MEMS inertial sensors. Currently capabilities include single-axis (x, y, z) accelerometers, dual-axis (xy, xz, yz) accelerometers, triaxis

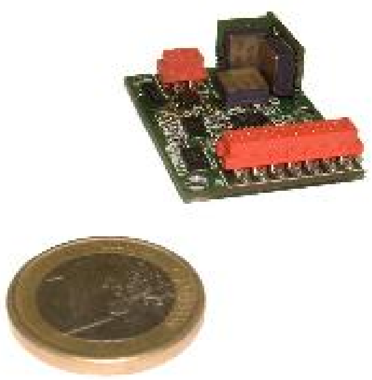

Fig. 2. Sensor provided by Technaid. This sensor is a combination of triaxial accelerometer, gyroscopes and magnetometer in order to provide six-degrees-of-freedom motion estimation.

accelerometers, low-g to high-g accelerometer capability, filtered analog and digital outputs, accelerometers (x, y, z) and angular-rate sensors/gyroscopes (x, y, z), gyroscopes in all three independent axes (x, y, z), low-rate and high-rate gyroscope capability, two-range sensing capability in one device on both gyroscopes and accelerometers. In addition, it is also available the combination of gyroscopes, accelerometers and magnetometer in one sensor, see figure 2. The sensor has analog and digital output. The digital output is made through an ADC (10bits / 12 bits) and the available connections are USB or SPI.

In order to evaluate the performance of the device developed to monitor and suppress tremor it was planned two studies:

- Assessment of biomechanical characteristics in upper limb tremorous movements.
- Reduction of tremor amplitude by means of WOTAS orthosis.

In the first study, 31 patients suffering from different tremor pathologies were evaluated and it was possible to estimate dynamics characteristics, such as power and energy, associated to the tremorous movement in each joint of the upper limb based on a biomechanical model of the upper arm, [12]. The biomechanical model has been build taking into account the Leva and Zatsiorsky and Seluyanov tables, [13]. These tables are one of the most widely accepted information within the field of biomechanics in order to perform dynamic analysis. In particular in sports and medical biomechanics. Leva adjustments have been made in order to define accurately the anthropometric measurements required to obtain inertial parameters from Zatsiorsky tables. A solid rigid model of the forearm has been build with the information taken from the above mentioned tables. The model has been parameterized using the Denavit- Hartenberg approach.

This analysis aims to estimate the torque and power of the tremorous movement in each joint of the upper limb based on the information provided by the gyroscopes. As said before, in tremor literature there is no reference regarding the amplitude of the torque associated to the tremorous movement and this information is very important in the design of powered orthosis for tremor suppression. Active orthosis aims to counteract tremor applying controlled forces. The torque is an essential parameter in the choice of the actuator technology that will be used by the powered orthoses. Special care should be taken to this parameter because, as can be seen in Figure 3 these torques present a dynamic behavior. The information provided by this study allows for the specification of tremor suppression orthosis actuators requirements.

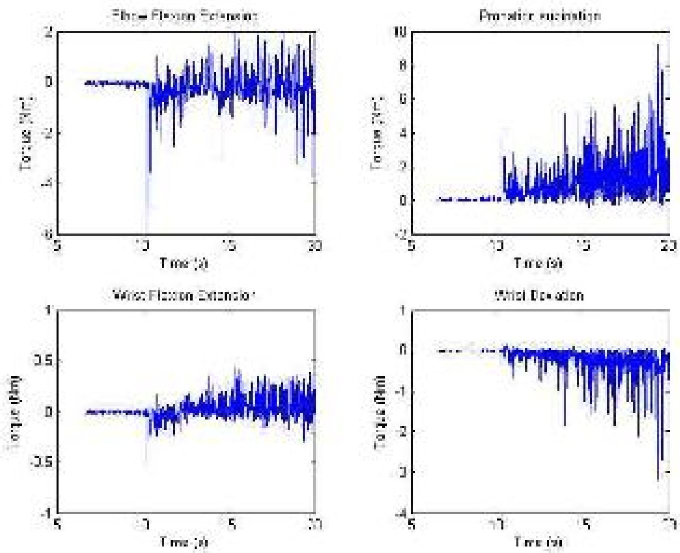

Fig. 3. Arm outstretched torques.

According to this study the mean value of torque required to suppress tremor in elbow flexo-extension and forearm pronation-supination joints is roughly 3 N.m while the mean value of torque necessary in wrist flexo-extension and deviation is 1 N.m. The other important parameter is the power that can be absorbed by the device. The amount of power consumption related with tremor is the one of the keys parameters to take into account in the design of these devices. The power at joint plus the performance of the devices will also determine the capacity of batteries. The joint where the power of tremor movement is bigger is in the prono-supination of the forearm and its value is roughly 2 W.

In the second experiment, the sensor based on gyroscopes presented was incorporated to the Wotas active orthosis for tremor suppression and an experimental setup involving 4 patients suffering from different tremor diseases. The experiments were realized in cooperation with Hôpital Erasme, in Belgium, and were led by a neurologist.

During the first clinical trials the system was able to measure and estimate tremor parameters, see upper parts of Figure 4. The capacity of applying dynamic internal forces to the upper limb for tremor suppression (based on the information provided by the inertial sensors) was evaluated. The output voltage coming from the gyroscopes was sampled at 2000 Hz rate. The data was filtered using a Kernel Smoothing algorithm and a gaussian window 51

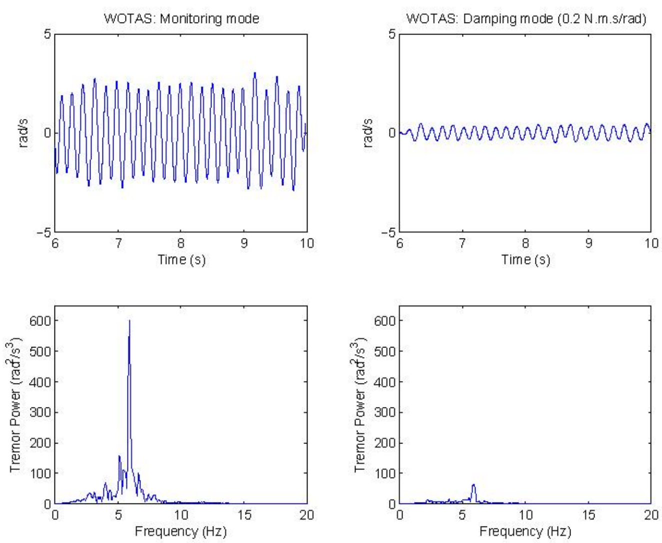

Fig. 4. The graphics illustrated the reduction in the tremor power when WOTAS is applying viscosity to the tremorous movement.

Fig. 5. Lower-limb exoskeleton for functional compensation of gait.

points width. The parameter chosen to estimate tremor level is the Power contained in the band from 2 Hz to 6 Hz. Based on this parameter it was found that the device could achieve a consistent 30% tremor power reduction, with reduction peaks in the order of 80% in the tremor power for patients exhibiting severe tremor [4], see Figure 4.

The proposed configuration based on rate gyroscopes has been demonstrated as a reliable sensor, with an associated low computational burden (suitable for real-time application) to calculate biomechanical variables as required in active orthotic devices. This system provides a novel and non invasive tool for tremor assessment and functional evaluation. In addition, it could measure the contribution of each joint to the overall tremor behavior.

III. Inertial measurement unit for control of lower limb exoskeletons.

A robotic lower limb exoskeleton (the GAIT exoskeleton) has been developed to enable functional compensation of people suffering muscle weakness around the knee and ankle joint [3]. The lower limb exoskeleton follows the kinematic structures of the leg and spans the knee and the ankle joints. The exoskeleton is equipped with a collection of kinematic and kinetic sensor to enable the ambulatory monitoring of pathological gait and to help evaluate progress of rehabilitation programmes, see figure 5.

In order to analize the feasibility of use inertial sensing to control leg orthoses/exoskeletons, during walking, for control and measurement purposes, triaxial inertial sensors combining rate gyroscopes and accelerometers have been fixed to the foot, shank and thigh segments of an unilateral orthotic device. The sensors signals are referred to a local coordinate system *XYZ*, which defines the rotational and longitudinal displacement axis of the limb-attached bars, along the coronal, sagittal and transversal planes, respectively (see figure 6).

Analysing the spectral estimation of 3D rotational velocities per orthotic segment during gait at natural cadence provides information required for real-time signal processing and control. Foot segment rotational velocities ω_i are presented in figure 7. Dominant peaks of frequency occur in w_x and ω_y, given that orthotic hinges impose restrictions of rotation along z axis. Based on this, for further estimation of angular acceleration of the foot at natural cadences, based on gyroscopes signal, a cutting frequency of 4 Hz is determined in a 4th order – zero phase Butterworth filter.

A particular application of orthotic control proposes inertial measurement units for compensation of human pathological gait with a robotic leg orthosis, composed by micromachined bi-axial accelerometers and a rate gyroscope, measuring foot and shank orthotic segments kinematics in a two dimensional configuration, [14]. Suiting units at the ankle and shank bars of the orthotic device enables sensing of rotational motion, tilt, tangential and radial segment accelerations in orthogonal directions (X and Y), while considering mechanical constraints imposed by common orthotic and prosthetic hinges. Considering the dynamics of muscle weakness gait patterns - average (2.6km/h) and low (2 km/h) speeds - it is proposed rejection of sensors signals outside the band frequency related to gait kinematics (0.3-20 Hz), from the sensor outputs with -3dB low pass filters, while lowering noise floor by bandwidth limiting. Besides, noise effects in sensors signals due to vibrations and shock impacts during motion are minimized while considering redundant information in the control approach of the robot, [14]. Angular acceleration of body segments can be calculated by numerical differentiation of angular rate. During dynamical conditions, segments orientation can be determined from angular velocities signals given by attached gyroscopes. Being $\vec{w}_i$, calculated angular rate, the orientation

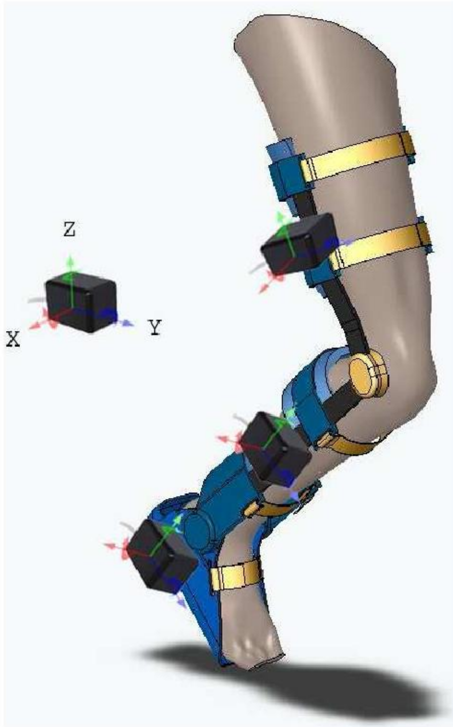

Fig. 6. Local reference system and inertial sensors setup in exoskeleton

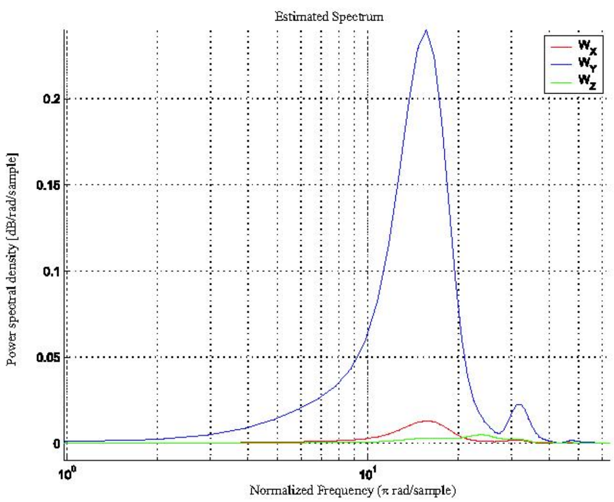

Fig. 7. Spectral estimation of the foot angular velocities signals w_i, based on Welch method, during normal gait with a leg orthosis at natural cadence

angle $\vec{\Theta}_i$ along i of the segment, can be calculated by numerical differentiation of the integral:

$$\vec{\Theta}_i = [\int_t \vec{w}_i.G_i] + \vec{\Theta}_i(0), \quad (1)$$

with G_i, as the sensor signal gain. Sensor signal offset and initial tilt can be calculated during initial static conditions, through tangential accelerometers signals, as proposed by [9], during being the acceleration approximately 1g. Error due to offset drift appears when applying 1, during prolonged periods. This can be corrected in cyclical activities like planar walking, with a resetting mechanism applied each cycle at

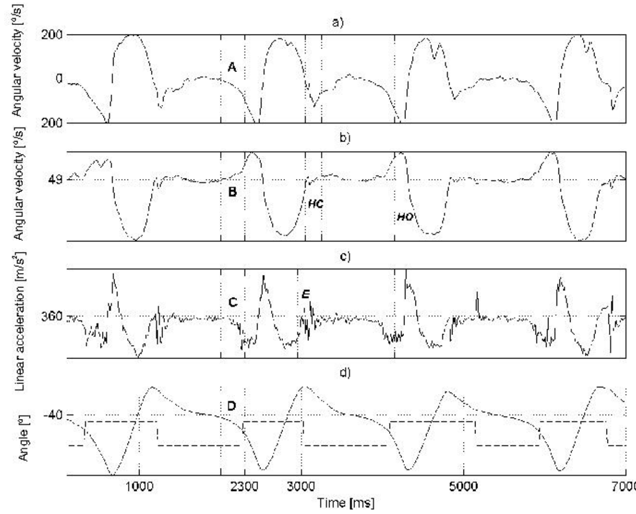

Fig. 8. Representative graphs of sagittal plane: (a) orthosis foot plate rotational velocity, (b) lower bar segment rotation velocity; (c) orthosis ankle part linear -*Y axis*- acceleration and (d) calculated ankle orthosis joint angle - solid line, for a sequence of four gait cycles of a subject wearing the orthosis prototype on level ground. Transition between controlled *stance* and *free swing* modes is used as (d) *reference* signal - dashed line. A, B and C represent periods of feasible and early detection for control. (Note: HC: heel-contact, HO: heel-off, KE: knee extension).

heel strike detection, obtainable from a tangentially oriented accelerometer at the foot.

Experiments were performed combining acquisition with an on-board processing unit at 100 Hz sampling frequency with simultaneous video recording. A healthy subject was asked to wear the orthosis prototype. During walking, this applied a different amount of resistance at the level of the joints, in two modes: stance mode (leg in contact with the ground) or free swing mode. The knee hinge was tuned to automatically switch between modes by mechanical means, allowing normal walking. The subject performed walking trials on level ground at low and normal speeds. Offset correction of all sensors is performed during static standing position.

Example of data obtained with both IMUs during four consecutive gait cycles at low speed is depicted in Figure 8. Accelerations measured by the IMUs along the longitudinal axis of the orthosis while walking, reach values within a range -dependant of gait speed- as a consequence of events such as heel contact, full foot stance and heel off from the ground. Gravity component is removed digitally.

Upon from foot bar longitudinal acceleration (Y axis) the leg deceleration and landing can be clearly distinguished. Zero acceleration at foot bar during stance and sign of linear rotation measured by the accelerometer feature a correlated pattern with shank acceleration component during stance and swing progressions.

With respect to gyroscope signals, from the shapes of cyclic patterns, events like heel contact (HC) and heel off (HO) can be extracted (Fig. 8.a). Using 1, ankle joint velocity is calculated and by cycle to cycle integration, joint angle is calculated. Continuous integration of the digitized gyroscopes signals results in drift error increasing in time (offset integrated as acceleration). Based on zero velocity detection by the inertial set, drift can be removed periodically. Thus, detection of terminal stance can be made, while dorsiflexion trajectories and shank bar forward progression prior swing of the leg can be quantified. Based on the information about the orthosis prototype working mode as reference, -sensed internally at the switching mechanism- (Fig 8.d), we identify the feasibility of early (tenths of milliseconds) and concomitant detection with IMU, based on (i) foot angular velocity during ankle dorsi flexion, (ii) angular velocity of lower bar while rotating forward and (iii) heel acceleration, while lifting the ground. Also the period when the subject relies primarily on the orthosis, can be quantified between HC and HO. The prototype returns to stance mode when orthosis knee extension (KE) is reached at the end of swing; once extension is achieved, IMU on the structure experiments peak acceleration, suitable for this detection means.

It has been concluded that upon from the IMU configuration, provide sufficient redundant information for control of a novel active system conceived for dynamically adaptation of orthotic joint impedance. Moreover, collection and enrichment of biomechanical data from the sensor setup can be obtained for motion analysis. Broadly in locomotion applications, different gait events as feedback inputs for prosthetic or orthotic control can be exploited from the proposed embodiment.

This small 2D inertial sensor can be used in several applications involving human limbs motion analysis and control of prosthetic and orthotic devices. The developed IMU provides broad information for both control and gait analysis in a wearable application, in this case, under the approach of a reactive algorithm to interact with the human body and improve locomotion. Mechanical constraints common in artificial limbs are used to simplify calculations while reducing the sensing degrees of freedom. Different attachments and combinations of IMUs might be adopted if a wearable device is suited to cross or replace several joints, e.g. hip orthosis, elbow-hand prosthesis, etc.

IV. Conclusions

The proposed biomechanical inertial sensor has been evaluated in two exoskeletons and has been found to be strongly dependant on the sensor alignment with the segment of interest. Sensors robust attachment and precise alignment are crucial as well as calibration procedures and drifts correction (e.g. temperature). Hence, this sensor is only applicable in rigid orthotic frames, since it could not provide accurate estimations when used directly on the skin. A possible alternative solution is to use additional gyroscopes to implement concomitant measurement of axis misalignment and consequently allow for online compensation. This is one of the research topics that will be pursued in the coming future.

State of the art MEMs sensors cover widely the range of requirements of the application dealing with normal and low speeds and while accelerations over the sensing range (full-scale +/- 2 g) are not expected.

The main advantages of this proposed sensor are simple electronics, light weight, low cost, easy adaptation to orthotic/robotic exoskeletal frame, low noise signals and low computational burden. These features make MEMS inertial sensing an attractive alternative when real-time biomechanical data is required. This tool provides a powerful tool to monitoring biomechanical variables suitable for application on orthotics and prothestics robotics.

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