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# ***International Journal of Mechanics and Control***

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The Journal is addressed to scientists and engineers who work in the fields of mechanics (mechanics, machines, systems, control, structures). It is edited in Turin (Northern Italy) by Levrotto&Bella Co., with an international board of editors. It will have not advertising.

Turin has a great and long tradition in mechanics and automation of mechanical systems. The journal would will to satisfy the needs of young research workers of having their work published on a qualified paper in a short time, and of the public need to read the results of researches as fast as possible.

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The *International Journal of Mechanics and Control* publishes as rapidly as possible manuscripts of high standards. It aims at providing a fast means of exchange of ideas among workers in Mechanics, at offering an effective method of bringing new results quickly to the public and at establishing an informal vehicle for the discussion of ideas that may still in the formative stages.

## ***Language: English***

*International Journal of Mechanics and Control* will publish both scientific and applied contributions. The scope of the journal includes theoretical and computational methods, their applications and experimental procedures used to validate the theoretical foundations. The research reported in the journal will address the issues of new formulations, solution, algorithms, computational efficiency, analytical and computational kinematics synthesis, system dynamics, structures, flexibility effects, control, optimisation, real-time simulation, reliability and durability. Fields such as vehicle dynamics, aerospace technology, robotics and mechatronics, machine dynamics, crashworthiness, biomechanics, computer graphics, or system identification are also covered by the journal.

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## **Preface for the special issue of the JoMaC dedicated to the 21<sup>st</sup> edition of the Workshop on Robotics in Alpe-Adria-Danube Region, RAAD 2013**

The aim of the International Journal of Mechanisms and Control (JoMaC) is to present and promote the latest scientific achievements in the fields of mechanism, control systems and complex structures. Starting from 2003, nearly every year one issue of the International Journal of Mechanics and Control has been devoted to selected papers from the annual RAAD workshop.

The RAAD workshops started in 1992 when we realized that enhancing international cooperation, focusing on neighboring countries and unifying resources was important.

And it is also becoming more and more important today. Since then RAAD workshop has been each year organized in one of the countries in the Alpe-Adria-Danube region: 1992 Portorož (Slovenia), 1993 Krems (Austria), 1994 Bled (Slovenia), 1995 Pörschach (Austria), 1996 Budapest (Hungary), 1997 Cassino (Italy), 1998 Smolenice (Slovakia), 1998 Munich (Germany), 2000 Maribor (Slovenia), 2001 Vienna (Austria), 2002 Balatonfüred (Hungary), 2003 Cassino (Italy), 2004 Brno (Czech Republic), 2005 Bucharest (Romania), 2006 Balatonfüred (Hungary), 2007 Ljubljana (Slovenia), 2008 Ancona (Italy), 2009 Brasov (Romania), 2010 Budapest (Hungary), 2011 Brno (Czech Republic), 2012 Naples (Italy), and in 2013 in Portorož (Slovenija).

The thrust of research in the field of robotics has gradually moved from classical industrial applications to the challenging areas of service and humanoid robotics. Globalization forces us to intensify the cooperation between researchers and developers in all fields of their activities, something that is especially important for small neighborhood countries. Here, the RAAD conferences play an important role for the community in the Alpe-Adria-Danube Region.

The RAAD conference got its name from the geographical region Alpe-Adria-Danube, but was never meant to be limited to participants coming solely from this region. This year, we had 50 papers from researchers who come from 20 different countries, which were accepted for publication in the Proceedings of the RAAD 2013. The topics coincide with the contemporary trends in robotics as well as with the RAAD tradition.

According to the tradition, we have prepared a special issue of the 22nd International Workshop on Robotics in the Alpe-Adria-Danube Region, RAAD 2013, organized in Pororož, Slovenia. The selection of the contributed papers is a result of a careful reviewing process among the best presented papers, which fit the scope of the journal. This special issue brings the latest results from mechatronic design, advanced control, medical and rehabilitation robotics, and covers many challenges from contemporary service and humanoid robotics. We are convinced the readers will find this selection of excellent papers valuable and inspiring. We also believe that this special issue will promote future RAAD conferences and enhance international cooperation and scientific dissemination in Alpe-Adria-Danube region and abroad.

Finally, we would also like to express our gratitude to everybody who contributed to this event, especially the RAAD International Scientific Committee for the support and help both in the organization of the Workshop as well as in the paper selection for this journal special issue:

- Nikos A. Aspragathos, University of Patras, Greece
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# WEARABLE SENSORY SYSTEM FOR ROBOTIC PROSTHESIS

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## ABSTRACT

The paper presents a wearable sensory system aimed at tracking of motion parameters and estimation of kinematic data of the wearer for use in controlling active lower-limb ortho-prostheses. The sensory system comprises inertial and magnetic measurement units (IMUs) attached to body segments and sensorized insoles worn inside sneaker shoes. Through sensory fusion, the IMUs data is used to produce estimates of segment orientations, while the insoles provide information on vertical ground reaction force amplitude and distribution. The paper outlines the principles of the algorithms and shows the evaluation of them. Algorithms use both reference and wearable sensory data to extract information about the subject's kinematics, movement type and phase and track selected biomechanical stability descriptors. The paper discusses preliminary experimental results of the proposed algorithms.

Keywords: Wearable sensors, Active prosthesis, Sensory Fusion, Movement identification, Phase segmentation, Stability tracking.

## 1 INTRODUCTION

Loss of a lower-limb can be a great obstacle in the life of persons following lower-limb amputation. It may affect the person's general health. Amputation can be performed at different levels, such as foot level, knee level or at the level of the thigh. Above-knee amputation is usually the most stressful of amputation types as it greatly diminishes the person's natural area of movement [1]. Persons following amputation tend to consume more metabolic energy than healthy persons and require greater level of mental effort to move their body without falling [2]. The goal of the EU-funded CYBERLEGs project (The CYBERnetic LowEr-Limb CoGnitive Orto-prosthesis) is aimed at development of a robotic, wearable ortho-prosthesis.

Since currently available passive and active prostheses do not greatly diminish effort and energy consumption, the aim of the project is the development of a cognitive robotic system for persons following above-knee amputation that enables them to perform previously demanding movement manoeuvres with minimal mental effort and energy consumption. The manoeuvres of interest are steady-state

ground-level walking, stair ascent and descent as well as sit-to-stand and stand-to-sit movement. Laboratory of Robotics at the Faculty of Electrical Engineering, University of Ljubljana is involved in development of a wearable sensory system, sensory fusion, cognitive decision making and intention detection algorithms alongside tracking of stability parameters during movements.

In laboratory environment, systems used for assessment of kinematics parameters are usually based on an optical principle with the use of passive (Vicon) or active markers (Optotrak) [3]. Such laboratory systems have high accuracy but they are large, expensive, stationary, and have limited measurement space. Recently, the use of inertial and magnetic sensor for assessment of human kinematics parameters has become a common practice [4], [5]. Inertial sensors are less accurate compared to laboratory systems, however, they are lighter, cheaper, wearable and do not alter natural movement patterns. As such they can also be used outside the laboratory environment.

Fusion of sensory signals from inertial and magnetic sensors placed on body segments is used to assess the segments' orientation. Kalman filtering is a common approach for this task, where orientation is estimated by integrating angular velocity [6], [7]. Due to the drift of integrated gyroscope output and temperature dependency, the orientation error tends to grow with time.

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To compensate for the error of integration, the integrated orientation estimate is fused with the orientation estimate obtained from accelerometer and magnetometer data.

The sensory system, via sensory fusion algorithms, should provide the cognitive system with information on the user's kinematic parameters while the cognitive system provides information about the user's current movement state and intention to the controller. Additionally, tracking of stability parameters should be incorporated into the cognitive system, in order to provide a basis for decisions on reactive movement when a sudden loss of balance is imminent.

This paper is divided into four parts that comprise the cognitive system of CYBERLEGS and build upon each other. The first section describes the wearable hardware used for extracting information on user movement and intention as well as body kinematic parameters. The second part describes the principles upon which the sensory fusion and extraction of kinematic parameters are based and also provides some preliminary evaluation data of the proposed algorithms. Based on sensory data, part three presents a cognitive machine that identifies current movement manoeuvre that user is performing and classifies phases within that particular movement type. The system provides data on steady states as well as transitions between these states. Furthermore, part four describes tracking of independent particular stability descriptive parameters are tracked based on a statistical anthropometric model, estimated kinematic parameters and directly measured sensory information.

## 2 WEARABLE SENSORY SYSTEM HARDWARE

The CYBERLEGS sensory and feedback system uses commercially-available components and custom-made sensing components, developed within the CYBERLEGS Consortium (see schematic shown in Figure 1). As the figure shows, the system comprises several wearable sensors - sensorized insoles, pressure-sensitive pads to measure human-robot interaction, inertial measurement units (IMUs), vibrotactile modules for afferent feedback and sensors for detection of amputee psychophysiological stress status - in addition to sensors for controlling the actuation system and measurement of the joint positions of the ortho-prosthesis. Communication with the main controller employs both UDP and SPI protocols, while sensory fusion runs on a separate real-time OS (xPC Target) based machine.

The inertial measurement units are used for assessing the orientation of human body segments, and shoe insoles for measuring ground reaction forces. The sensory data acquisition unit consists of two wireless receiver units (RU) for fetching data via 802.15.4 (ZigBee) and Bluetooth protocols. Transfer of acquired data employs Ethernet UDP communication to the controller that runs the tools for data processing and sensory fusion algorithms.

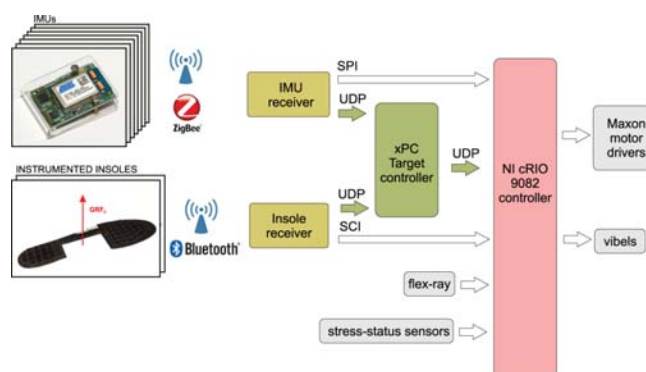


Figure 1 CYBERLEGS wearable sensory system: sensors and data acquisition unit.

### 2.1 SENSORIZED INSOLES

The CYBERLEGS pressure-sensitive insoles, developed at Scuola Superiore Sant' Anna, Pisa, Italy [8], comprise an array of 64 pressure sensors and fit into normal sneaker shoes. Each cell has a working range from 0 to 70 N. They are wireless, run on battery power and output vertical ground reaction force estimate as well as a distribution of this force along the sole (Centre of Pressure - COP).

### 2.2 INERTIAL MEASUREMENT SYSTEM

An inertial and magnetic measurement unit (Figure 2) consists of three sensors which measure 3D vectors of angular velocity (range  $\pm 500$  °/s), translational acceleration (range  $\pm 2$  G), and magnetic field (range  $\pm 1.3$  Ga) and is equipped with an on-board 8-bit processor [9]. The size of the IMU without the battery is  $30 \times 20 \times 5$  mm. For measuring kinematic parameters of the human body, seven IMUs are used. Each of the IMU is placed on an individual segment of lower extremities: feet, shanks, thighs, and trunk. Placement of the IMU on the segment is determined with initial evaluation of IMU orientation during standstill.

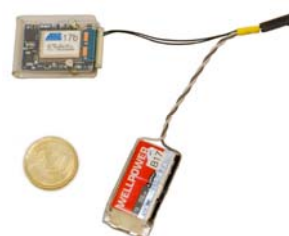


Figure 2 Inertial measurement unit with a battery.

## 3 ASSESMENT OF KINEMATIC PARAMETERS

Kinematics of the human body can be estimated using data provided by wearable sensors. Based on sensory signals from seven IMUs, we have developed an algorithm for kinematics parameters assessment by means of sensory data fusion.



A common approach for determining segment orientations is the use of an Unscented Kalman filter applied to the measurement data [9]. The approach is based on individual segment's angular velocity integration during motion and orientation correction with respect to gravity and the Earth's magnetic field. The accelerometer is used as an inclinometer by comparing measured acceleration vector to the vector of gravity in order to determine the intermediate angle of inclination. For successful implementation of the magnetometer into the algorithm it is assumed that magnetic field in space is locally constant (constant direction and length) and non-parallel to gravity. Considering this assumption, the angle of rotation around the gravity vector can be calculated by comparing the measured magnetic vector with the initial vector of the magnetic field.

The approach often results in a drift during long-term dynamical movement due to gyroscope drift, errors introduced by separation of gravity and dynamic acceleration and changes of the magnetic field. To compensate for this effect, resetting during standstill was introduced. In order to further reduce the drift without the need for standstill, a kinematic model of the human body was incorporated into the sensory fusion algorithm.

To determine joint angles that describe relative position between segments, an error quaternion between two adjacent segments is calculated and presented with rotation angles as shown in Figure 3.

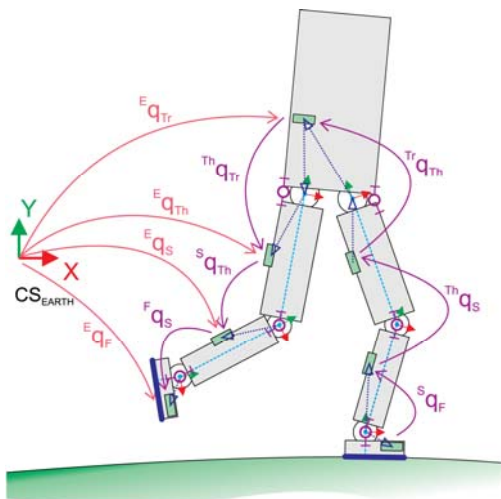


Figure 3 Calculation of body kinematic parameters.

Other parameters which can also be obtained with the presented wearable system (e.g. step duration, gait frequency, acceleration of centres of mass, etc.) exceed the scope of this paper.

#### 4 MOVEMENT CALSSIFICATION AND PHASE DETECTION

In literature, authors presented segmentations for different movement types: ground-level walking [10], walking over obstacles [11], stair climbing [12], sit-to-stand and stand-to-sit [13]. A threshold-based decision tree was developed for

performing recognition of ground level walking with gait phases, stair ascent and descent and stand-to-sit and sit-to-stand manoeuvre based on wearable sensory data. In Figure 4 a conceptual state diagram with all the possible transitions between detected manoeuvres and gait phases is presented.

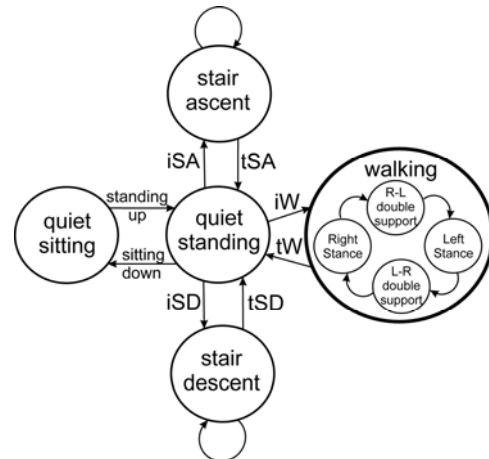


Figure 4 A conceptual diagram of the detected set of movement types and transitions; iW - initiation of walking; iSA - initiation of stair ascent; iSD - initiation of stair descent; tW - termination of walking; tSA - termination of stair ascent; tSD – termination of stair descent.

The decision tree was tuned off-line to perform movement identification and intention detection as well as phase segmentation within recognized manoeuvres. The algorithm was tested with healthy subjects online, in real-time. Results show that while this approach is successful for recognition of movement types, it is sensitive to unexpected behaviour. For this reason, a more robust, state-machine architecture for the algorithm was built. This approach allows transitions between states to occur only when they satisfy a number of specific conditions. The transition threshold values may be defined manually while specific conditions and the general order of magnitude of these values remain unchanged. On the other hand, this makes the classification and segmentation machine less tailored to a specific wearer of the sensory system.

As an alternative, a fuzzy logic approach was utilized. The approach resulted in creating soft (fuzzy) transition rules for the state-machine with the use of fuzzy clustering method. The method outputs probability with which the fused sensory data best fits a given signal cluster [14]. The centres of each cluster were taught before-hand, offline. Probability is calculated as the distance to each of the centres.

#### 5 TRACKING OF BALANCE DESCRIPTORS

The human body is a multi-body system, supported by only one or two relatively small segments, which results in a fairly small supportive polygon. This polygon is a convex hull that includes all points of contact between the body and the outside world. Human posture is defined by reciprocal relationships of human-body segments and their orientation

with respect to the Earth's inertial frame. One of the goals of the CYBERLEGS project is to track estimates of particular balance descriptors using only data derived from wearable sensors.

Two balance descriptors were chosen for tracking: the whole body Centre Of Mass (COM) and the Zero-Moment Point (ZMP - a point on the ground where the horizontal components of the resultant moment are equal to zero).

The COM is determined from kinematic parameters of the user and warrants knowledge of mass and inertial parameters of particular segments of the human body. Thus, the segmental COM positions are estimated according to segment orientations and statistically-determined human body anthropometrical data [15].

The ZMP can either be measured (when the resultant horizontal moment is balanced) or estimated from a combination of kinematic and inertial data. The derivation of ZMP through forward kinematics is based on moment equilibrium in the ground plane, following Equation (1) [16]:

$$M_R = [0 \ 0 \ 0]^T = \sum_{i=1}^n (\vec{r}_{COM,i} \times (m_i \cdot \vec{a}_i) + I_i \cdot \dot{\omega}_i + \omega_i \times (I_i \cdot \omega_i)) - \vec{r}_{COM,i} \times m_{body} \cdot \vec{g} + \left( \sum_{i=1}^n m_i \cdot \vec{a}_i - m_{body} \cdot \vec{g} \right) \times \vec{r}_{ZMP} \quad (1)$$

The index  $i$  denotes the  $i$ -th segment,  $m_i$  mass,  $\omega_i$  and  $\dot{\omega}_i$  angular velocity and acceleration, respectively.  $I_i$  is the segment's inertia matrix, while  $\vec{r}_{COM,i}$  and  $\vec{r}_{ZMP}$  denote vectors of segment COMs (former) and ZMP (latter).

The proposed algorithms build upon assumptions, which introduce some limitations to the accuracy of the estimates. They assume that all body segments are non-compliant, the ground is rigid and level and no sliding or slipping occurs. Furthermore, all anthropometric and kinematic information is assumed known [16].

## 6 EXPERIMENTAL EVALUATION

Experimental data was collected in experiments with multiple subjects performing walking, stair climbing and sit-to-stand manoeuvres. Using NDI Optotrak 3D optical position measurement system, spatial positions of active infrared markers, attached to bony landmarks of the subject's body, were measured. Linear and angular velocities as well as accelerations were either derived from 3D position data (only dynamic acceleration) or directly measured by the inertial measurement units, placed on the subject's body segments. In the latter case, each IMU was equipped with three IR markers, relaying information on placement position and orientation to the investigators. During the walking manoeuvre, data from sensorized

insoles was collected in order to determine foot-ground contact times and estimates of vertical ground reaction force and centre of pressure. Two IR markers were positioned at the side of the shoe soles to estimate (with knowledge of the sole outline with respect to these markers) the contact hull of support for each foot. Sensor placement is shown in Figure 5. Experimental validation of the wearable system for measuring movement kinematics of healthy subjects was performed by comparison of orientations obtained from IMUs with data acquired by the Optotrak system.

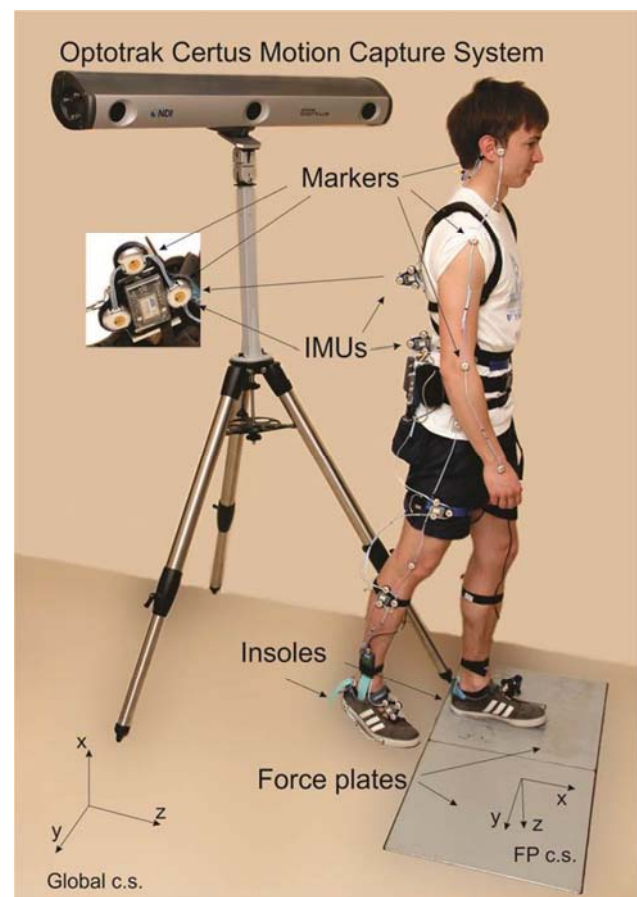


Figure 5 Experimental evaluation: reference system (Optotrak Certus and force plates) and wearable sensors (IMUs and insoles).

### 6.1 DETECTION OF WALKING PHASES

Initial testing and validation was performed for the walking manoeuvre. Figure 6 shows results of online recognition for the walking manoeuvre with gait phases using a hard-coded state-machine and fuzzy clustering method.

Results of preliminary comparison show more robust performance of the state-machine algorithm, while fuzzy logic offers easier adjustments to an individual subject. Currently, the fuzzy clustering method requires the clusters to be defined offline, based on a learning set, before applying them to the classification and segmentation engine.

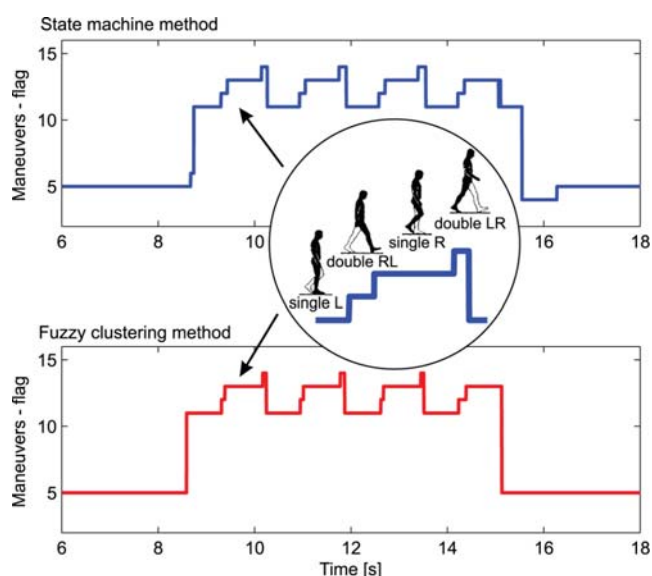


Figure 6 Results of manoeuvres and gait phase detection, comparing two different approaches (above: state machine, below: fuzzy logic clustering).

## 6.2 MOTION KINEMATICS TRACKING IN STANDING-UP

Experimental validation of the wearable system for measuring movement kinematics of healthy subjects was performed by comparison of joint angles obtained from IMU with data acquired by a reference measurement system (Optotrak). Joint angles were derived from measured positions of markers placed on bony landmarks of the subject's body.

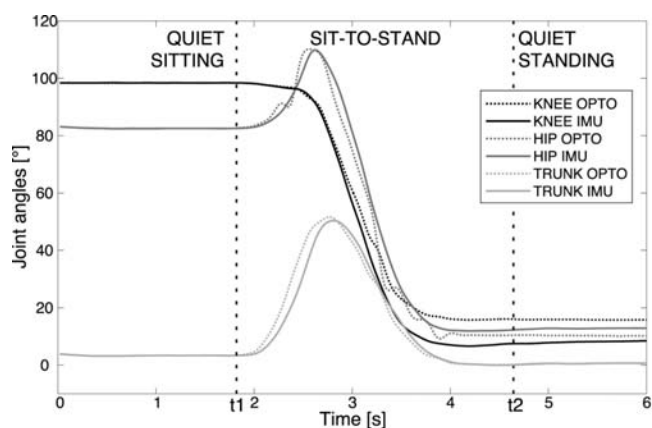


Figure 7 Typical knee and hip angles and trunk inclination during standing up, obtained with reference system (OPTO) and wearable system (IMU). Times  $t_1$  and  $t_2$  denote the start and finish of standing up, respectively.

Five IMUs were placed on body segments (shanks, thighs and trunk) along with IR active markers for position reference. Joint angles were obtained with decomposition of error quaternions between two segments. The algorithm was evaluated with experiments in standing-up and sitting-down of a healthy subject. Experimental protocol involved

several repetitions of sit-to-stand and stand-to-sit motion during three-minute-long measurements. Typical joint angle trajectories (knee and hip angles and trunk inclination) derived from Optotrak- or IMU-based data, respectively, are presented in Figure 7.

Statistical comparison of joint angles (knee and hip joint angle and trunk inclination angle) is presented in Figure 8 with boxplots of absolute error between angles obtained from the Optotrak system and those from the wearable system. Results show that the median value of absolute error of the wearable system is below  $2^\circ$  and is as such appropriate for measuring kinematics parameters.

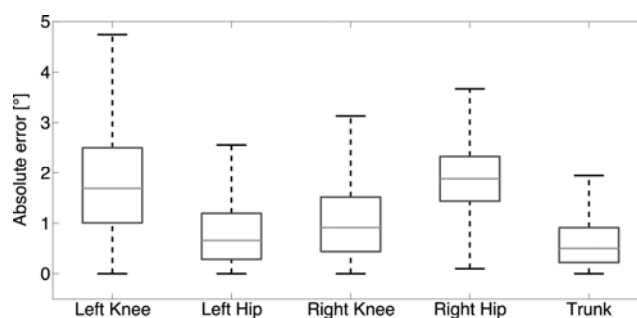


Figure 8 Boxplot of absolute error between joint angles calculated from IMU data and angles calculated from Optotrak data.

## 6.3 BALANCE DESCRIPTORS

For the stair climbing manoeuvre, the trajectories of the ZMP point, measured by the reference force sensors implemented in ground and stairs, were compared to the ZMP trajectory estimated from position-derived data. Seven healthy subjects performed multiple barefoot walks up the stairs. Results showed a combined RMSE error of 54 mm, thus proving the concept of ZMP assessment by a kinematics-based approach for a human subject in motion [17].

An algorithm that combines data provided from position sensors with data, collected by wearable sensors, was used to yield sample-based balance descriptor estimates with respect to a desired coordinate frame origin. Estimates of COM and ZMP trajectories from combined sensory data for a 4-step walking manoeuvre are shown in Figure 9.

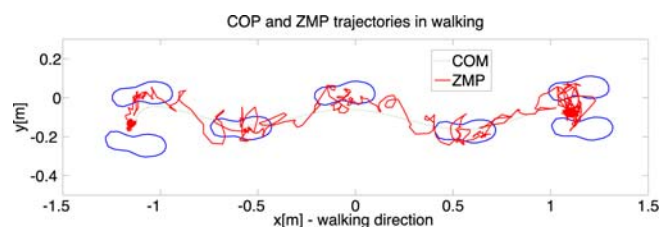


Figure 9 ZMP and COM trajectory with respect to the feet support for a 4-step walking manoeuvre with quiet standing at the beginning and the end of walk.

Preliminary results indicate that balance descriptors estimated from a combination of sensors are equally descriptive as those derived solely from position data. In addition, by combining subject kinematics with data from

the insoles, we are able to track the instantaneous base of support. As a result, the ZMP stability margin (minimal distance from the edge of the support polygon) can be assessed on-line.

Figure 10 shows one slow walk with 4 steps, starting and ending while the subject is in quiet standing. Stability is quantified as the distance from the closest point in which the resultant moment on the body, acting in the plane of the ground support, can be balanced by a resultant force applied to the ground by the subject. Depending on whether this point lies within the base of support or outside of it, the point is termed ZMP or Fictitious ZMP, respectively. The distance from the closest edge of the support polygon is positive when the resultant force should be applied outside and negative when inside the instantaneous base of support.

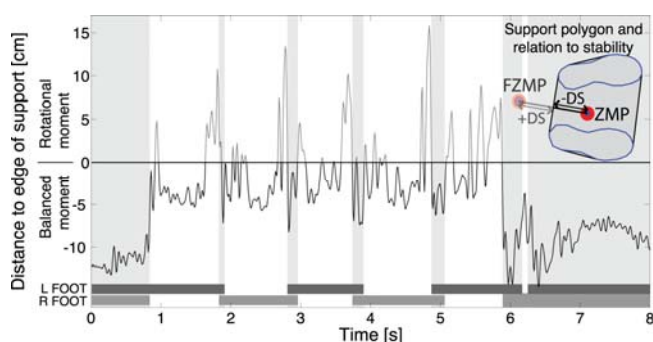


Figure 10 Assessed stability in terms of minimal distance of the ZMP from the edge of the support polygon. Negative values denote situations where the ZMP lies within the base of support while positive values convey the distance of the FZMP (a point outside of the support polygon) to the edge of the base of support. The bottom lines show contact times of the left and right foot, respectively. Grey patches over the entire figure mark double support instances, while white space marks single stance of a foot.

Preliminary investigation suggests that most of the unbalanced moment (tipping about the edge of support) is present at times of beginning and end of single support - that is right after toe off and right before heel strike of the swing leg. This conforms to the idea that humans take advantage of physical dynamics of the body during steady-state gait with regard to swing foot placement [18] and react to unbalanced moment by moving parts of the body that are not in contact with the environment and thus maximize stability [19].

## 7 CONCLUSIONS

This paper presents the sensory system for robotic ortho-prosthesis which is based on wearable sensors incorporating the inertial measurements units and sensorized insoles worn by the subject. Data from the wearable system is fused by sensory fusion algorithms to assess the human body motion kinematics, identify motion manoeuvre and its phases, and track stability descriptors.

The algorithm for motion kinematics assessment is based on Extended Kalman filtering and fuses the integral of angular velocity with the estimate of linear acceleration, based on kinematic model of the human body. Experimental validation of the algorithm was accomplished on healthy subject performing sit-to-stand manoeuvre. Comparison of joint angles, assessed by wearable system, with those obtained from reference position measurements results in absolute error median smaller than  $2^\circ$ . The results confirm the suitability of wearable system for joint angles assessment in dynamic situations. Additionally, performance of detection of manoeuvres and gait phases was tested online, exploiting both measured and estimated data. Two different algorithms were developed and evaluated. A decision tree with threshold based rules generally performs more robust detection, while the fuzzy clustering method is more convenient when the acquisition of training data sets is possible. Furthermore, fuzzy clusters can be tailored to each subject. Making use of a statistical anthropometric model, segmental centres of mass and the estimated ZMP position, the support polygon was assessed and the ZMP stability margin quantified for ground level walking. Results suggest that most of the unbalanced moment (tipping over the edge of support) is present at instants of beginning and end of single support phase. This suggests that humans take advantage of physical dynamics of the body during steady-state gait, thus exhibiting globally stable gait.

In future developments, the presented contributions will be combined to form a unique sensory system for motion parameters tracking based on wearable sensory data only.

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## REFERENCES

- [1] K. Hagberg and R. Brånemark, Consequences of non-vascular trans-femoral amputation: a survey of quality of life, prosthetic use and problems. *Prosthetics and orthotics international*, vol. 25, no. 3, pp. 186-194, 2001.
- [2] W. C. Miller, M. Speechley, and B. Deathe, The prevalence and risk factors of falling and fear of falling among lower extremity amputees. *Archives of physical medicine and rehabilitation*, vol. 82, no. 8, pp. 1031-1037, 2001.
- [3] C. Kirtley, *Clinical gait analysis: theory and practice*. Churchill Livingstone, 2006.
- [4] P. Bonato, Wearable sensors/systems and their impact on biomedical engineering. *IEEE Engineering in Medicine and Biology Magazine*, vol. 22, no. 3, pp. 18-20, 2003.

- [5] D. Roetenberg, H. Luinge, and P. Slycke, *Xsens MVN: full 6DOF human motion tracking using miniature inertial sensors*. Xsens Motion Technologies BV, Tech. Rep, 2009.
- [6] A. M. Sabatini, Quaternion-based extended Kalman filter for determining orientation by inertial and magnetic sensing. *IEEE transactions on bio-medical engineering*, vol. 53, no. 7, pp. 1346-56, Jul. 2006.
- [7] X. Yun and E. R. Bachmann, Design, implementation, and experimental results of a quaternion-based Kalman filter for human body motion tracking. *IEEE Transactions on Robotics*, vol. 22, no. 6, pp. 1216-1227, 2006.
- [8] S. M. M. De Rossi et al., Development of an in-shoe pressure-sensitive device for gait analysis. *Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 2011, pp. 5637-5640.
- [9] D. Novak, P. Rebersek, T. Beravs, J. Podobnik, and M. Munih, Development and validation of a wearable inertial measurement system for use with lower limb exoskeletons. *Proceedings of IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*, 2011, pp. 212-217.
- [10] M. W. Whittle, *Gait analysis: an introduction*. Butterworth-Heinemann, 1996.
- [11] T. Li, M. Ceccarelli, T. Essomba, M. A. Laribi, and S. Zeghloul, Analysis of human biped obstacle overcoming by motion capture system. *Presented at the international Workshop on Robotics in Alpe--Adria--Danube Region 2012 (RAAD 2012)*, 2012, pp. 85-92.
- [12] B. J. McFadyen and D. A. Winter, An integrated biomechanical analysis of normal stair ascent and descent. *Journal of biomechanics*, vol. 21, no. 9, pp. 733-744, 1988.
- [13] A. Kralj, R. J. Jaeger, and M. Munih, Analysis of standing up and sitting down in humans: definitions and normative data presentation. *Journal of biomechanics*, vol. 23, no. 11, pp. 1123-1138, 1990.
- [14] S. Gagula-Palalic, *Fuzzy Clustering Models and Algorithms for Pattern Recognition*. International University of Sarajevo, 2008.
- [15] P. De Leva, Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of biomechanics*, vol. 29, no. 9, pp. 1223-1230, 1996.
- [16] M. H. P. Dekker, *Zero-Moment Point Method for Stable Biped Walking*. Internship report DCT Nr.: 2009.072, 2009.
- [17] L. Ambrozic, *Analiza biomehanskih parametrov pri hoji po stopnicah*. Bachelor thesis, University of Ljubljana, 2012.
- [18] J. S. Matthis and B. R. Fajen, Humans exploit the biomechanics of bipedal gait during visually guided walking over complex terrain. *Proceedings of the Royal Society B: Biological Sciences*, vol. 280, no. 1762, 2013.
- [19] T. Robert, B. C. Bennett, S. D. Russell, C. A. Zirker, and M. F. Abel, Angular momentum synergies during walking. *Experimental brain research*, vol. 197, no. 2, pp. 185-197, 2009.



# TEMPLATE FOR PREPARING PAPERS FOR PUBLISHING IN INTERNATIONAL JOURNAL OF MECHANICS AND CONTROL

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## ABSTRACT

This is a brief guide to prepare papers in a better style for publishing in International Journal of Mechanics and Control (JoMaC). It gives details of the preferred style in a template format to ease paper presentation. The abstract must be able to indicate the principal authors' contribution to the argument containing the chosen method and the obtained results. (max 200 words)

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## 1 TITLE OF SECTION (E.G. INTRODUCTION)

This sample article is to show you how to prepare papers in a standard style for publishing in International Journal of Mechanics and Control.

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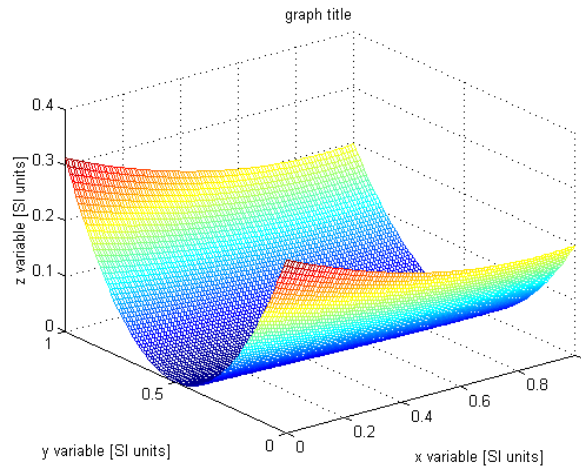


Figure 1 Simple chart.

Table VII - Experimental values

Robot Arm Velocity (rad/s)	Motor Torque (Nm)
0.123	10.123
1.456	20.234
2.789	30.345
3.012	40.456

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