2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

Mini-Symposia Title:

Recent Advances in Wearable Sensing and Machine Learning for Biomechanics - B

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Ben Sanchez, Ph.D., University of Utah, USA

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Kathleen Denis, Ph.D., KU Leuven, Belgium

Mini-Symposia Speaker Name & Affiliation 6

Steve Collins, Ph.D., Stanford University, USA

Theme:

- ○ 01.Biomedical Signal Processing
- ○ 02.Biomedical Imaging and Image Processing
- ○ 03. Micro/Nano-bioengineering; Cellular/Tissue Engineering & Biomaterials
- ○ 04. Computational Systems & Synthetic Biology; Multiscale modeling
- ○ 05. Cardiovascular and Respiratory Systems Engineering
- ○ 06. Neural and Rehabilitation Engineering
- ◉ 07. Biomedical Sensors and Wearable Systems
- ○ 08. Biorobotics and Biomechanics
- ○ 09. Therapeutic & Diagnostic Systems and Technologies
- ○ 10. Biomedical & Health Informatics
- ○ 11. Biomedical Engineering Education and Society
- ○ 12. Translational Engineering for Healthcare Innovation and Commercialization

Mini-Symposia Synopsis – Max 2000 Characters

A large portion of the population in the United States and around the world suffer from musculoskeletal injuries and disorders that result in a large number of patient visits, surgical procedures, and arduous rehabilitation protocols. The current paradigm for diagnosing and monitoring such injuries and disorders hinges on a combination of expensive and time-consuming procedures such as the physical examination by a trained physician, physical therapist, or athletic trainer, or medical imaging such as MRI or CT. A major challenge is that, while rehabilitation and treatments may pervade for many weeks or months—and thus therapies should ideally be tailored to meet the changing needs of patients—both physical exam and medical imaging procedures are only suitable to clinical settings, and do not lend themselves to serial measurements that can be used to provide closed-loop therapies and / or titration of care. Wearable sensing systems with associate machine learning algorithms for deriving important measures of joint health hold merit for potentially shifting this paradigm of care for persons with musculoskeletal injuries or disorders. This second session of the proposed mini-symposium will focus on challenges towards successful deployment and operation in clinical settings, and opportunities for digital health information.

Electrical Bioimpedance Alterations Resulting from Eccentric and Concentric Activity Profiles

Todd J. Freeborn, *Member, IEEE*

Abstract— **Localized electrical bioimpedance measurements capture the passive electrical properties of a tissue. Recent efforts applying this technique have quantified alterations in bicep tissue bioimpedance resulting from activity profiles with concentric/eccentric movements and eccentric-only movements. This aims to increase understanding the alterations of tissues typical of many rehabilitative activities. While reported results support that localized tissue bioimpedance show decreases in impedance magnitude as a result of exercise/fatigue/injury, differentiating underlying physiological mechanisms from these measurements requires further study.**

I. Introduction

Electrical bioimpedance measurements quantify the passive electrical properties of a biological tissue which are dependent on the cell population, cell volumes, cellular membrane integrity, and the intra / extra cellular fluids [1]; all of which are related to the health status of the tissue. These measurements are attractive for monitoring because they do not present any high radiation risks to patients, are non-invasive (only requiring surface electrodes on the tissue for their collection), with potential to be integrated into flexible and wearable systems. Such advances would enable continuous monitoring for days, weeks, and months that could prove revolutionary as a tool for the study and management of neuro-muscular diseases, management of fatigue/over-exertion/injury, and personalization of rehabilitation strategies.

II. Exercise-Induced Alterations

Advancing the application of tissue bioimpedance for monitoring rehabilitation requires further understanding of how exercise, fatigue, injury, and recovery alter these measures of skeletal muscle. Recent efforts have quantified alterations in localized bicep tissue bioimpedance as a result of activity profiles with concentric/eccentric [2] movements and eccentric-only [3] movements. Both activity profiles reduced tissue resistance and reactance by more than 8% but have different time-courses of change. The concentric/eccentric protocols resulted in observable differences between immediate pre/post activity timepoints, while differences in the eccentric-only protocol were not observed until timepoints 48h and 72h after activity. This may be a result of the metabolic differences that exist between the two types of contractions. Eccentric contractions have been reported to require lower muscle activation for greater force output in studies using surface electromyography and also have a lower energy cost compared to concentric activity [4]. Differences in the impedance alterations may suggest that concentric activity has a greater vasodilatory stimulus and increased blood flow more than the eccentric activity (for a similar stimulus). Increased blood flow may account for the impedance decreases that were observed immediately after a protocol with concentric and eccentric activation). While the impedance decreases observed in the participants 48h and 72h after the eccentric protocol may be attributed to swelling from tissue damage and inflammation [3]. While the time-course of bioimpedance alterations for the activity protocols were different, the fact that alterations from both were observed as decreases in impedance magnitude make utilizing bioimpedance measurements alone challenging to identify the specific mechanism (e.g. blood/fluid change, or tissue damage/inflammation) of the alterations.

III. Future Research

While efforts are exploring the use of equivalent circuit modeling to identify markers that may be more strongly associated with different physiological mechanism of change (e.g. capacitive features of equivalent models as markers of tissue damage [5]), there is also an opportunity to explore multi-model data fusion in this space. Comprehensive assessment of skeletal muscle using bioimpedance, muscle activation, and activity context with data fusion and machine learning algorithms could identify the feature set that can accurately differentiate mechanisms of physiological change, the activities that induced these changes, and track recovery. This could provide a path forward to support the generation of clinically-relevant and actionable data for personalized rehabilitation using data collected during free-living.

References

[1] S. Grimnes and O. Martinsen, Bioimpedance and Bioelectricity Basics, 3rd Ed., Academic Press, London, 2000.

[2] T.J. Freeborn, B. Fu, "Time-course bicep tissue bio-impedance changes throughout a fatiguing exercise protocol," *Med. Eng. Phys.*, vol. 69, pp. 109-115, 2019.

[3] T.J. Freeborn, G. Regard, B. Fu, "Localized bicep tissue bioimpedance alterations following eccentric exercise in healthy young adults," *IEEE Access*, vol. 8, pp. 23100-23109, 2020.

[4] M. Muthalib, H. Lee, G. Y. Millet, M. Ferrari, and K. Nosaka, ''Comparison between maximal lengthening and shortening contractions for biceps brachii muscle oxygenation and hemodynamics,'' *J. Appl. Physiol*., vol. 109, no. 3, pp. 710–720, 2010.

[5] B. Fu, T.J. Freeborn, "Cole-impedance parameters representing biceps tissue bioimpedance in healthy adults and their alterations following eccentric exercise," *J. Adv. Res*., vol. 25, pp. 285-293, 2020.

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Ubiquitous Computing, Machine Learning, and Modeling and Simulation for Biomechanics Research

Bjoern M. Eskofier, Senior Member, IEEE, Anne D. Koelewijn, and Martin Vossiek, Fellow, IEEE

Abstract— **Different fields are continually contributing new methods and systems to biomechanics research. Among the three most prominent are ubiquitous computing, machine learning, and modeling and simulation. This contribution will highlight each of these three, and concretely address novel research questions, methods and applications thereof.**

INTRODUCTION

Different fields are continually contributing new methods and systems to biomechanics research. Among the three most prominent are ubiquitous computing, machine learning, and modeling and simulation.

Ubiquitous computing systems play an increasingly important role in biomechanics and related research areas [1]. Wearable computing and external, for example camera- or wave-based (radar, microwave), measurement systems can provide real-time data, potentially supporting feedback, performance improvement and injury reduction. They also allow to instrument biomechanical studies outside the lab, facilitating the assessment of the real, “in-the-wild”, situation.

Machine learning and data mining concepts provide data-driven tools for analyzing the considerable amount of data that is generated in biomechanics studies, especially using the above-mentioned ubiquitous computing systems [2, 3]. Traditional statistical analysis methods commonly cannot handle this amount of data easily. Thus, the analysis is often restricted to individual variables rather than multidimensional dependencies and a considerable amount of information is neglected. Moreover, the results are frequently biased by the expectation of the researcher. Using machine learning and data mining concepts, researchers can address these challenges. These concepts have the ability to deal with large data sets, to analyze multiple dimensions simultaneously, to work data-driven rather than hypothesis-driven, and to provide valuable insights into training effects and injury risks.

Modeling and simulation are essential to analyze human motion and interaction [4, 5]. A lot of research questions are not directly addressable by experimentation, which is due to either ethical reasons or measurement challenges. Using mathematical, biomechanical models, reality can be simulated using controllable boundary conditions. In this setting, objectivity and reproducibility are inherent, which provides acceptable model validity. A challenge is to find an optimal compromise regarding model complexity and modeling accuracy.

The talk targets interested scientists in the areas of sports technology and biomechanics. Novel research questions, methods and applications thereof will be presented. range from. The main objective of the talk is to bridge the gap between scientists with expertise on technological state-of-the-art and scientists that might apply such technologies but often do not realize their potentials or are not aware how to apply them. Also addressed will be future research directions.

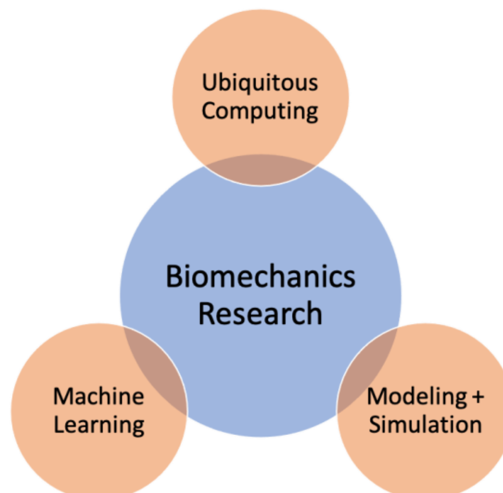

Figure 1. Ubiquitous Computing, Machine Learning, and Modeling and Simulation for Biomechanics Research.

REFERENCES

[1] BM Eskofier, SI Lee, M Baron, A Simon, CF Martindale, H Gaßner, J Klucken, “An Overview of Smart Shoes in the Internet of Health Things: Gait and Mobility Assessment in Health Promotion and Disease Monitoring”, Applied Sciences 7, 986-1002, 2017.

[2] BM Eskofier, P Federolf, P Kugler, BM Nigg, “Marker-based classification of young-elderly gait pattern differences via direct PCA feature extraction and SVMs”, Computer Methods in Biomechanics and Biomedical Engineering, 16(4), 435-442, 2013.

[3] T Kautz, BM Eskofier, C Pasluosta, „Generic Performance Measure for Multiclass-Classifiers”, Pattern Recognition 68, 111-125, 2017.

[4] M Nitschke, E Dorschky, D Heinrich, H Schlarb, BM Eskofier, AD Koelewijn, AJ Van den Bogert, „Efficient trajectory optimization for curved running using a 3D musculoskeletal model with implicit dynamics”, Nature Scientific Reports, 10: 17655, 2020.

[5] E Dorschky, M Nitschke, C Martindale, AJ Van den Bogert, AD Koelewijn, BM Eskofier, „CNN-based Estimation of Sagittal Plane Walking and Running Biomechanics from Measured and Simulated Inertial Sensor Data”, Front Bioeng Biotech, 8: 604, 2020.

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Tracking spatial, temporal and balance metrics for variable gait using only three inertial measurement units

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***Abstract*— we proposed and evaluated a three IMU wearable sensor configuration for daily-life monitoring of variable gait.**

I. Introduction

Monitoring spatial, temporal and balance aspects of variable gait during daily-life is required in people with central neurological disorders that affect gait, like stroke and Parkinson's disease. Such monitoring should be minimally obtrusive, available at any place and time, and provide relative movement of the feet and CoM. Previously, we proposed to use instrumented shoes for analysis of variable gait [1, 2], applying the extended Center of Mass (XCoM) versus Base of Support (BoS) concepts of Hof et al. [3], and demonstrated these concepts in the analysis of variable gait in people with stroke [1, 2]. These shoes included high-quality 3D force sensors, which are bulky and impede non-obtrusive application in daily-life. Our recent research proposed and evaluated an alternative minimally obtrusive sensor set for this purpose.

II. Methods

We propose a configuration of three inertial measurement units (IMUs), one on the pelvis and one on each foot, and to apply the Centroidal Moment Pivot (CMP) theory as a biomechanical constraint regarding the relative distances between foot and CoM [4]. We presented methods to estimate the ground reaction force vector (GRF) and relative positions of both feet and CoM as a function of time in a body-centric reference frame [5, 6]. We also proposed a method to estimate the ground reaction force vector in a body-centric frame using only one sensor on the pelvis [7].

III. Results

Error of estimated instantaneous 3D GRF was 12.1 ± 3.3% in the horizontal plane across variable walking tasks [6]. Errors in estimating step lengths and width during variable gait tasks were 4.6 ± 1.5 cm and 3.8 ± 1.5 cm [5]. The method was able to distinguish step length asymmetry during asymmetrical gait.

IV. Discussion & Conclusion

The proposed methods have potential for daily-life monitoring of variable gait and are currently being evaluated in stroke.

Research supported by Netherlands organization of Scientific Research (NWO), Perspectief, neuroCIMT, 14905. Peter H. Veltink: P.H.Veltink@utwente.nl.

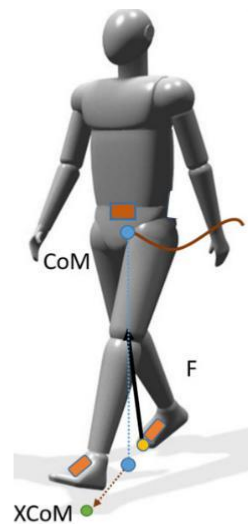

Figure 1. Three IMU sensor configuration (orange rectangles) for monitoring spatial, temporal and balance aspects of variable gait [5, 6]

References

[1] F. B. van Meulen, D. Weenk, J. H. Buurke, B. J. van Beijnum, and P. H. Veltink, "Ambulatory assessment of walking balance after stroke using instrumented shoes," *J Neuroeng Rehabil,* vol. 13, no. 1, p. 48, May 19 2016.

[2] F. B. van Meulen, D. Weenk, E. H. van Asseldonk, H. M. Schepers, P. H. Veltink, and J. H. Buurke, "Analysis of Balance during Functional Walking in Stroke Survivors," *PLoS One,* vol. 11, no. 11, p. e0166789, 2016.

[3] A. L. Hof, M. G. Gazendam, and W. E. Sinke, "The condition for dynamic stability," *J Biomech,* vol. 38, no. 1, pp. 1-8, Jan 2005.

[4] M. B. Popovic, G. A., and H. Herr, "Ground reference points in legged locomotion: Definitions, biological trajectories and control implications," *Int. J. Rob. Res.,* vol. 24, no. 12, pp. 1013-1032, 2005.

[5] M. I. Mohamed Refai, B. F. van Beijnum, J. H. Buurke, and P. H. Veltink, "Portable Gait Lab: Tracking Relative Distances of Feet and CoM Using Three IMUs," *IEEE Trans Neural Syst Rehabil Eng,* vol. 28, no. 10, pp. 2255-2264, Oct 2020.

[6] M. I. M. Refai, B. F. van Beijnum, J. H. Buurke, and P. H. Veltink, "Portable Gait Lab: Estimating 3D GRF Using a Pelvis IMU in a Foot IMU Defined Frame," *IEEE Trans Neural Syst Rehabil Eng,* vol. 28, no. 6, pp. 1308-1316, Jun 2020.

[7] M. I. Mohamed Refai, B. F. van Beijnum, J. H. Buurke, and P. H. Veltink, "Portable Gait Lab: Estimating Over-Ground 3D Ground Reaction Forces Using Only a Pelvis IMU," *Sensors (Basel),* vol. 20, no. 21, Nov 7 2020.

IoT-enabled device and analytics for continuous mental stress monitoring

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Abstract— **Stress is a health concern worldwide. Persistent stress can lead to musculoskeletal injuries and acute medical conditions, including hypertension and stroke, and it remains most commonly responsible for long-term absence at work. The application of innovative wearable biosensing technologies can help to managing stress in the workplace, providing insights about employee stress levels and its impact on individuals, and alleviating costs to the economic system on a global scale.**

I. Introduction

Stress plays a critical role in our lives, from childhood affecting our acquisition of knowledge and skills, to adulthood when the requirements of the job do not match the capabilities or needs of the worker [1]. At the work place, continuous stressful exposure to demanding workload over a long period of time without sufficient recovering can lead to harmful work-related musculoskeletal disorders resulting in long-term absence. These disorders occurring in the workplace have negative impact on the USA workforce and they are responsible for an economic loss that exceeds 250 billion annually [2]. In the UK, the New Economics Foundation analyzing hospital admission data from 2016/2017 discovered that there were 17,500 episodes where stress or anxiety was the primary cause for hospital admission. This led to 165,800 days where beds were occupied due to stress or anxiety, at a cost to the taxpayer of £71.1 million. In all, 526,000 workers suffered from work-related stress, depression or anxiety in 2016/17 leading to 12.5 million working days lost in the UK only. As our nations now struggle to emerge from the global COVID-19 pandemic, one critical consideration to address is how labor productivity is being undermined by stressful work conditions.

Today, physical examination plays a major role in assessing stress-induced work-related musculoskeletal disorders; however, it is subjective and can be sufficiently misleading so as to encourage an individual to return to work prematurely, compromising recovery and leading to re-injury. Imaging and neuromuscular tests are objective, can assess the anatomic site of the injury and they are not affected by the subject' cooperation or subjective impression of the examiner. Magnetic resonance imaging techniques such as diffusion tensor imaging and T2 mapping can assess muscle health on a molecular level. Ultrasound is another tool available that can quickly image muscle and tendon tear by measuring focal or diffuse regions of increased ultrasound echointensity. Despite the value of these existing tools, these technologies require the use of highly-trained personnel and are only available in a clinical setting. Perhaps more importantly, magnetic resonance imaging and ultrasound only find use when these disorders are clinically manifested and it is too late to take precautionary measures.

Here, we present a novel device that will enable robust preventive decision-making monitoring stress and anxiety at work.

II. Methods

The device supports two primary bio-sensing functions based of body bio-signals, namely the electrocardiogram and electrodermal measurements. The bio-sensing functions can be activated individually and simultaneously providing more resolution and accuracy to the readings from the body.

III. Results

The device developed enables real time data logging capability during daily activities. The utilization of all functions opens up an extremely large selection of features and analytics to assess stress and anxiety.

IV. Discussion & Conclusion

We have developed a fully functioning IoT monitoring device capable of simultaneously measuring a range of biomedical vital signs from the body and enabling automatic analytics of stress and anxiety. This device is our first step towards developing a new range of medically accurate algorithms, for both real-time and long-term data collection, that will truly enable continuous health monitoring in a broad range of application which is currently not possible with existing research tools outside of a lab environment.

References

[1] H. Yaribeygi, Y. Panahi, H. Sahraei, T. P. Johnston, and A. Sahebkar, "The impact of stress on body function: A review.," *EXCLI J.*, vol. 16, pp. 1057–1072, 2017.

[2] J. P. Leigh, "Economic Burden of Occupational Injury and Illness in the United States," *Milbank Q.*, vol. 89, no. 4, pp. 728–772, Dec. 2011.

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Vibro-acoustic assessment of orthopedic implant fixation

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Abstract— **This paper gives an overview of the vibro-acoustic techniques used at KU Leuven for the assessment of fixation of orthopedic implants. Techniques have been developed for intra-operative and for post-operative applications.**

I. Introduction

The intra-operative stability of cementless total hip replacement (THR) implants is achieved by press-fitting the implant in the bone and is a critical factor in determining the implant's life time [1]. *This stability is currently determined by the surgeon's subjective experience and can therefore be challenging for inexperienced surgeons or during the treatment of complex cases.* In total knee replacement (TKR), one of the key indications for revision is aseptic loosening. In its initial phase, aseptic loosening has no clinical symptoms making it difficult to detect [2]. *A more timely diagnosis of aseptic loosening could lead to medical recommendations to prevent further loosening or, if needed, to a timely scheduled revision, preventing irreparable damage to the host bone.*

II. Total Hip Replacement

To assist surgeons to achieve optimal intra-operative implant stability, our research group is developing real-time vibro-acoustic measurement methods to assess the implant fixation. Our work has demonstrated that these vibration-based methods allow monitoring the implant stability and can indicate the optimal endpoint of insertion non-destructively in real time. These methods have been validated in vitro using both artificial and cadaveric bone models and in vivo during surgery [3]. Vibro-acoustic approaches have been investigated to address the clinical challenges related to contact-based mechanical vibration measurements. The use of an acoustic approach led to promising results both in vitro [4] and in vivo during a series of recent clinical experiments [5]. One of the key research findings that is part of the development of the above-mentioned vibro-acoustic methods is the addition of customized vibro-acoustic instruments to the bone-implant system. These instruments lead to a substantial improvement of the vibro-acoustic method in terms of measurability and sensitivity.

III. Total Knee Replacement

The feasibility of vibration-based methods as a radiation-free alternative to existing methods for the fixation assessment of the tibial component was investigated in vitro using sawbones. Medial, lateral and peripheral loosening was simulated using a waxed plastic layer between the cement and implant or cement and bone. Modal analysis was performed on the bone-implant systems, showing different behavior of the loosened cases with respect to the fully fixed cases. Then a measurement strategy was developed using only excitation and measurement locations that are accessible post-operatively, enabling clinical implementation. Measurements taken proximally or at the medial malleolus showed feature differences in case of loosening. The experimental study was complemented with FE studies to investigate the sensitivity of the method [6]. The simulations used a validated model of an artificial tibia equipped with an implant and a cement layer. Damping was added similar to that of cadaveric bone. Different loosening situations were investigated. Results were in good agreement with the in vitro studies. Sensitive vibration-based features were identified that correlated well with the different fixation conditions. The method showed to be more sensitive to detect loosening between bone and cement than between cement and implant. The proposed methods need further validation using cadaveric bones.

IV. Conclusion

Vibro-acoustic techniques showed potential both in intra-operative and in post-operative assessment of orthopedic implant fixation. In THR, vibro-acoustic techniques can provide the surgeon with decision-supporting information during implant insertion. Moreover, results indicate that these techniques can help avoiding intra-operative fractures. In TKR, vibro-acoustic techniques show promising results regarding post-operative assessment of the fixation of tibial implants. Experimental results indicate that if a reference measurement of the unaffected situation is available, implant loosening is detectable together with an indication of the loosening location. More research is needed to investigate the influence of soft tissue surrounding the implant and of different loosening types.

References

[1] S. Gheduzzi, A. Miles. "A review of pre-clinical testing of femoral stem subsidence and comparison with clinical data." *Proc Inst Mech Eng, Part H: J Eng Med,* 2007, pp 39–46.
[2] K. Ren et al,. "Therapeutic intervention for wear debris-induced aseptic implant loosening,". *Acta Pharm Sin B*. 2013, pp. 76-85.
[3] L.C. Pastrav et al, "In vivo evaluation of a vibration analysis technique for the per-operative monitoring of the fixation of hip prostheses." *J Orthop Surg and Res,* 2009, pp 1-10.
[4] Q. Goossens et al. "An acoustic measurement method to assess acetabular implant stability in cementless total hip replacement", *Int Conf Sound Vib*, 2019, Montreal, Canada, p. 8.
[5] Q. Goossens et al, "Acoustic analysis to monitor implant seating and early detect fractures in cementless THA: An in vivo study." *J Orthop Res*, 2020, doi 10.1002, jor.24837.
[6] S. Leuridan et al, "Vibration-based fixation assessment of tibial knee implants: a combined in vitro and in silico feasibility study," *Med Eng Phys*. 2017, pp. 109-120.

*Research funded by KU Leuven Internal Funds.

Accurately monitoring energy expenditure with wearable sensors

Patrick Slade, Mykel Kochenderfer, Scott Delp, and Steve Collins, Stanford University

I. Introduction

Physical inactivity is the fourth leading cause of global mortality [1]. Health organizations have requested a tool to objectively measure physical activity. Respirometry and doubly labeled water accurately estimate energy expenditure but are infeasible for everyday use. Smartwatches are portable but have significant errors [2]. Self-report surveys and step counting are also commonly used but have significant errors.

Here, we present a wearable system that estimates metabolic energy expenditure in real-time during common steady-state and time-varying activities with substantially lower error than state-of-the-art methods. The wearable system uses inertial measurement units (IMUs) worn on the shank and thigh because they distinguished lower-limb activity better than wrist or trunk kinematics and converged more quickly than physiological signals.

II. Methods

We performed experiments to select sensors, collect training data, and validate the Wearable System with new subjects and new conditions for walking, running, stair climbing, and biking. We first performed an experiment to collect data from a variety of walking and running conditions and wearable sensors for offline testing (n = 13). Next, we collected additional data during stair climbing and biking using the selected IMU sensors on the shank and thigh (n = 10). The Wearable System consisted of a linear regression model trained with the data from these initial experiments. The final experiment validated the accuracy of the Wearable System with a new and physiologically diverse group of subjects during different conditions of walking, running, stair climbing and biking (n = 24).

III. Results

Initial experiments collecting a wide range of wearable sensor measurements revealed that two IMUs placed on the shank and thigh of one leg were the most informative.

During the validation experiment the Wearable System had a cumulative error of 13% across common activities, significantly less than 38% for a smartwatch and 52% for an activity-specific smartwatch. The Wearable System also accurately estimated energy expenditure during time-varying conditions transitioning between standing, walking, and running with step or sinusoidal changes in speed.

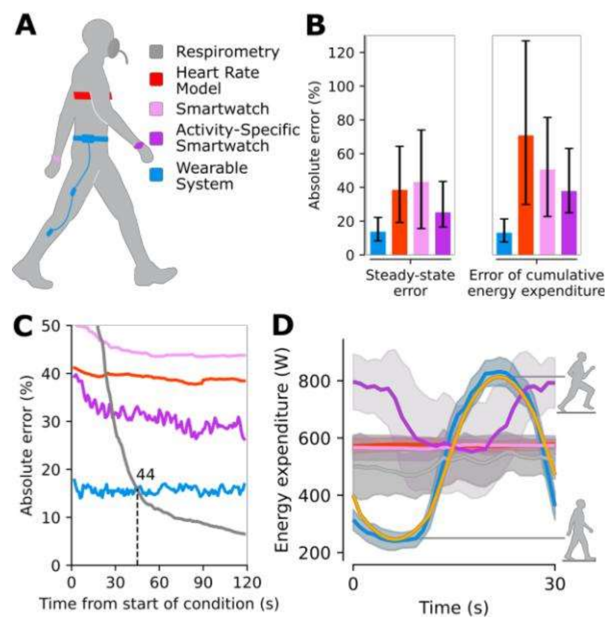

Figure 1. An overview of the accuracy of estimating energy expenditure with wearable sensors. (A) We compared the Wearable System's accuracy to other methods of estimating energy expenditure. (B) The Wearable System had the lowest steady-state and cumulative error across all steady-state activities including walking, running, stair climbing, and biking. (C) The Wearable System had low error from the start of the each condition, while methods relying on physiological signals took longer to reach a steady-state error. (D) The Wearable System was also able to accurately track energy expenditure during time-varying conditions shown in orange.

IV. Discussion & Conclusion

The accuracy of the Wearable System indicates inertial measurements of the leg relate closely to whole-body energy expenditure during common activities. Using the gait cycle structure of motion and IMU data allows for rapid estimates once per step [3], accurately capturing energy expenditure during steady-state and time-varying motion. This approach could enable new energy balance systems for weight management or tools for large-scale activity monitoring.

References

[1] *Global health risks: mortality and burden of disease attributable to selected major risks* (World Health Organization, Geneva, Switzerland, 2010).

[2] Shcherbina, Anna, et al. "Accuracy in wrist-worn, sensor-based measurements of heart rate and energy expenditure in a diverse cohort." *Journal of personalized medicine* 7, (2017).

Slade, Patrick, et al. "Rapid energy expenditure estimation for ankle assisted and inclined loaded walking." *Journal of neuroengineering and rehabilitation* 16.1 (2019): 1-10.

*Research supported by NSF GRFP, Stanford Graduate Fellowship.

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