An overview of wearable sensing and wearable feedback for gait retraining

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Abstract. Wearable gait retraining could enable benefits from laboratory retraining systems to extend to a broad portion of the population, which doesn't live near or have access to laboratory gait retraining testing facilities. While few portable gait retraining systems utilize both wearable sensing and wearable feedback, several systems employ critical components. The purpose of this paper is to provide a brief overview of various wearable sensing or wearable feedback components for gait retraining. We discuss wearable inertial sensors including accelerometers, gyroscopes, and magnetometers to estimate gait kinematics, wearable haptic feedback for retraining gait kinematics, wearable goniometers for measuring 2D and 3D ankle kinematics, and wearable measures of foot force and foot pressure. We conclude with a forward look at the future of wearable gait retraining systems and possible applications.

Keywords: Real-time training, rehabilitation, gait, feedback

1 Introduction

Technological advances in computing power have enabled human movement to be measured and relevant biomechanical parameters to be calculated in real-time. Concurrently, wearable haptic (touch) feedback devices have been shown to be particularly effective for informing humans to move in new ways. By combining real-time motion sensing with real-time haptic feedback, humans can in theory be trained to move in ways that prevent injury, increase athletic performance, or treat musculoskeletal or neurological disease. This is the essence of real-time movement training. Real-time movement training has often been used for relatively slow movements, such as upper extremity reaching tasks where the haptic feedback can provide direct feedback regarding trajectory errors [1], [2], [3]. Recent research has shown that real-time feedback can be used to train relatively faster movements such as gait [4], [5], [6]. However, most real-time gait retraining systems do not provide wearable sensing and wearable feedback [7], but rather are performed in a laboratory

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setting with equipment which is tethered to the ground. While this type of biofeedback has been clinically effective, such as reducing knee loading and pain for knee osteoarthritis patients [8], the benefits are limited to populations living near facilities equipped with the necessary and specialized equipment. Thus, wearable gait retraining systems could provide the same benefits seen in the laboratory to a much wider population. While few portable gait retraining systems with both wearable sensing and wearable feedback exist, several systems have employed necessary components. The purpose of this paper is to provide a brief overview of various systems with either wearable sensing or wearable feedback for gait retraining. We discuss wearable sensor arrays of accelerometers, gyroscopes, and magnetometers to estimate gait kinematics, wearable haptic feedback for training gait kinematics, wearable goniometers for measuring 2D and 3D ankle kinematics, and finally, wearable measures of foot force and foot pressure. We conclude with a forward look at the future of wearable gait retraining systems and possible applications.

2 Overview of Real-Time Movement Retraining

Real-time movement retraining through wearable systems requires several components: human user, sensing, real-time biomechanics model, desired biomechanics, and feedback (Fig. 1).

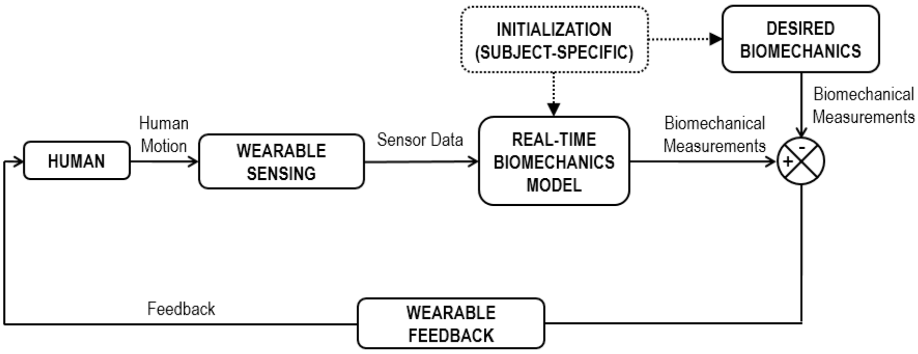

Fig. 1. Block diagram and information flow for real-time movement retraining systems.

Human movements are sensed with wearable sensors such as accelerometers, gyroscopes, or goniometer (more details in Section 3), and this data is sent to the real-time biomechanics model. The model converts sensor signals into relevant biomechanical parameters of interest. The model could be as simple as a unity gain or as complex as a full-body musculoskeletal real-time simulation. Sensed biomechanical measurements and then compared with the desired biomechanical measurements and the error signal is used to provide wearable feedback to the user to alert a movement correction. Additionally, the real-time biomechanics model and the desired biomechanics may be initialized in a way that is specific to each subject, though this is optional and could also be the same for all subjects. It is also possible for the real-time biomechanics model and the desired biomechanics to be updated throughout testing [9]. While the above block is general for any movement retraining, it is relevant for gait retraining in this paper.

3 Wearable Sensing and Feedback for Gait Retraining

While there are many types of wearable sensors for measuring human movement parameters, we choose to highlight some of the most common including: inertial sensors, goniometers, foot force, and foot pressure sensors. We also highlight wearable auditory and haptic feedback for informing kinematic gait changes.

3.1 Accelerometers, gyroscopes and magnetometers

Accelerometers, gyroscopes and magnetometers are miniaturized motion sensors that can be seen in many mobile devices such as smartphones and tablets. These sensors are responsible for sensing orientation when you tilt your smartphone and your device display rotates accordingly. Over the last few decades, Micro-Electro-Mechanical Systems (MEMS) technology has been responsible for the dramatic advance of these types of motion sensors. The sensors have become smaller, cheaper, more energy efficient, and more accurate. However, this type of sensor still has some shortcomings.

Accelerometers can sense the accelerations of an object it is attached to. Typically, accelerometers have higher signal-to-noise ratio at high frequencies than at low frequencies. Thus, position estimate at higher frequencies will yield a better result than at low frequencies where bias error from small to no movement becomes an issue. Gyroscopes can sense angular rates, or rate of turning, of an object. By integrating the signal, orientations (roll, pitch, and yaw angles) can be computed for a given object. However, over time, gyroscope signal drift error accumulates and results in reduced accuracy. Magnetometers can sense the earth's magnetic fields strength. Similar to a compass, it can be used to calculate the North Pole direction as an absolute reference direction. Magnetometers are susceptible to signal interference when ferrous material is present nearby. Due to some of these shortcomings, researchers usually use accelerometers, gyroscopes, and magnetometers in combination to improve overall performance. When accelerometers and gyroscopes are packaged together, they are sometimes called inertial measurement units (IMUs), and when all three sensors are present, some may refer to them as MARG (magnetic, angular rate, and gravitational) sensor. By combining multiple sensors together, we can achieve better performance than from each sensor alone through sensor fusion algorithms. Over the years, many algorithms have been developed and implemented to help improve the accuracy such as various kinds of Kalman filters [11, 15, 16, 17] or machine learning algorithms [12]

Due to their small size, portability, high accuracy, and low power consumption, these types of body-fixed sensors give rise to the possibility of bringing gait-lab quality measurements outside the traditional laboratory settings [10]. Several systems have been developed over the years, both wired and wireless. For example, Simcox et al. [13] developed a wired body-fixed sensor pack using accelerometers and gyroscopes to measure the trunk and lower-limb sagittal plane angles, as seen in Fig. 2A. Similarly, Watanabe et al. [18] developed a wireless version of this type of system that can also be used to estimate the stride length. In addition, some researchers have developed calibration procedures and algorithms to accurately measure three dimensional knee angles, which is particularly important for evaluating the knee anterior cruciate ligament (ACL) injury [14]. The challenge in using these miniaturized motion sensors lies in finding a robust sensor fusion algorithm that can achieve good accuracy over a long period of time.

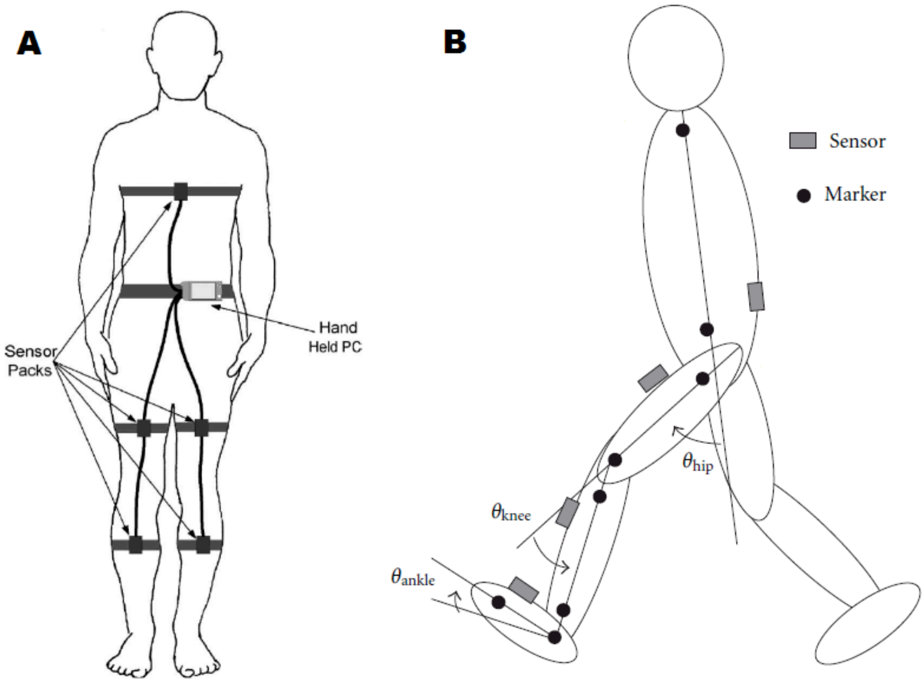

Fig. 2. A.) Wired body-fixed sensor packs. Image modified from [13]. B.) Placement of inertial sensors on the human body with joint angles definitions. Image modified from [18].

3.2 Wearable Feedback

Compared to wearable sensing, there are relatively fewer studies employing wearable feedback for gait retraining. The most common human sensations for wearable feedback of gait retraining are auditory and haptic, while vision, sight, and smell are less common. Basaglia et al. [19] used audio biofeedback to control knee recurvation during gait for patients with neurological diseases. An electrogoniometer was used to measure knee flexion angle and an audio signal alerted the user when knee flexion exceeded a threshold of 180 degrees. Riskowski et al. [20] used an instrumented knee brace to provide auditory biofeedback for the rate of loading. Once the rate of loading exceeded a specified threshold during gait an auditory signal would be sent to the user to alert a needed change. Shull et al. [4,21] retrained trunk sway, tibia angle, and foot progression angle by placing a wearable skin stretch device [22] and/or C2 tactor vibration motors near the location of desired kinematics change (Fig. 3). Wheeler et al. [23] strapped a vibration motor to the forearm to give feedback on the knee adduction moment (estimate of medial compartment loading). This alerted the user to choose a kinematic change to reduce the knee adduction moment. Finally, Dowling et al. [24] used a vibration motor on the shoe to retrain foot center of pressure during gait, which in turn changed the knee adduction moment.

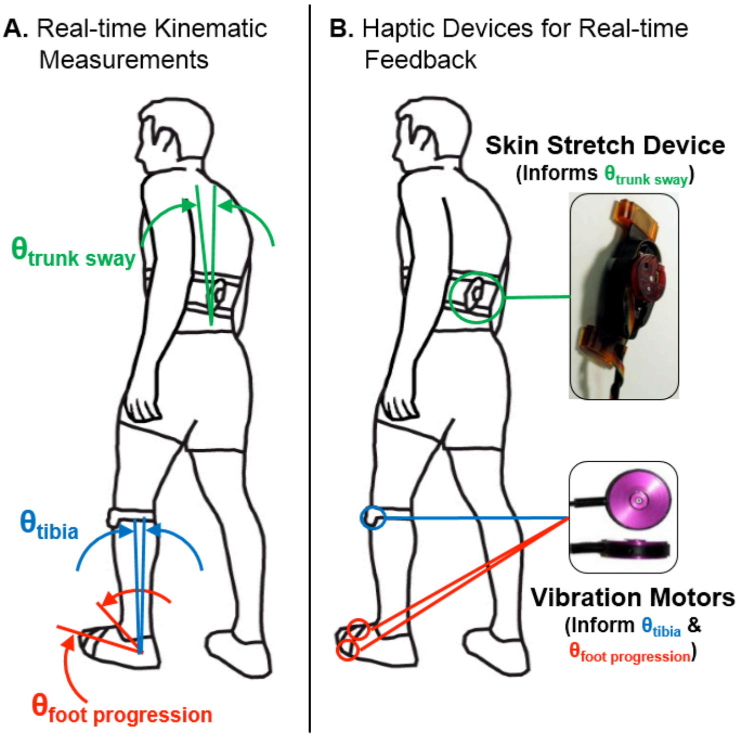

Fig. 3. (A) Real-time sensing and (B) haptic feedback to retrain gait kinematics. A rotational skin stretch device [22] on the lower back applies rotational skin stretch via two contact points on the skin to inform lateral trunk sway adjustments. One vibration motor on the lateral knee joint and two motors on the foot inform lateral tibia angle and foot progression angle, respectively. Image modified from [4].

3.3 Goniometers

Goniometers have long been used to measure human kinematics [25], [26]. Unlike some inertial sensors such as accelerometers or gyroscopes, which require integration to obtain kinematic positions, goniometers directly measure angular changes. There are several types of goniometers sensing elements: potentiometer, strain gauge, mechanical-flexible, inductive, and optical. Rigid goniometer sensing is most often performed with one or more potentiometers located at the desired axis of interest (Fig.

4). Alternatively, flexible goniometers use strain gauges, changes in elongation between multiple wires, and optical fiber to measure changes in bending angles.

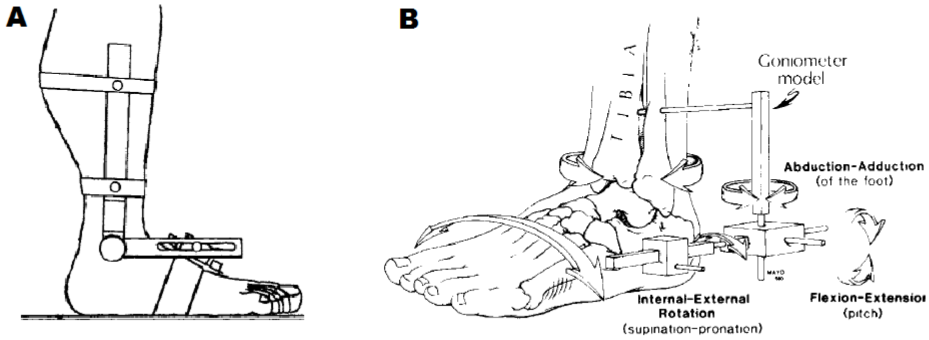

Fig. 4. (A) One degree-of-freedom goniometer to measure ankle flexion-extension. Image modified from [25]. (B) Three degree-of-freedom goniometer to measure ankle flexion-extension, internal-external rotation, and abduction-adduction. Image modified from [26].

3.4 Foot Force and Pressure

In a typical gait laboratory, there are usually force plates embedded into the ground or underneath a treadmill to measure ground reaction forces. This measurement allows researchers to analyze different walking characteristics such as their center of pressure and joint forces and moments via inverse dynamics. In order to obtain the same measurements outside the gait laboratory, researchers have developed several systems to capture ground reaction forces and moments or other correlated parameters [28, 31].

One simple version of foot force sensing comes in the form of force-sensing resistors (FSRs), seen in Fig. 5B. As its name suggested, the resistance changes as the force changes. Despite the non-linearity of the signal FSRs are quite robust and accurate for gait phase detection such as foot strike, swing, and stance [27]. For pathological gait disorders, the detection may become more difficult and less accurate. Still, FSRs have proven to be useful in many other applications. Redd et al. [32] developed FSR-embedded insoles to be used with a smartphone and successfully induced gait asymmetry in normal subjects. This may lead to the possibility of using it in rehabilitation for patients with asymmetry problem. De Leon Rodriguez et al. [33] demonstrated the use of in-shoe foot pressure sensing to minimize the new at-risk foot area for diabetes patients.

A high accuracy version of foot force measurement unit is a miniaturized force plate, as seen in Fig. 5A. This type of sensor gives more information than FSRs do. It can measure three axes of forces and three axes of moments, thus providing the researchers with the ability to estimate joint forces and moments when coupled with other motion sensors such as IMUs [30]. However, the higher accuracy and more information do not come without cost. The sensor cost is in the order of several thousands dollars or more for one unit. Furthermore, the weight of these instrumented force plate shoes is still relatively high and has a slight effect on normal gait [29]. The challenge with this type of sensor lies in the tradeoff among its accuracy of measurement, cost, weight, robustness, and ease of use.

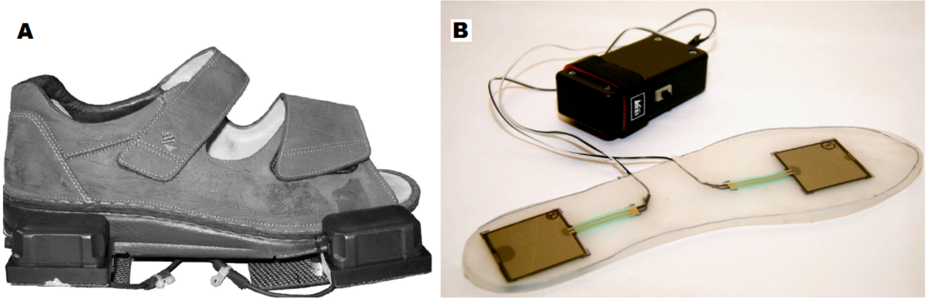

Fig. 5. A.) Instrumented shoe with miniaturized force plates and inertial measurement units (IMUs). Image modified from [30]. B.) Force-sensing resistors (FSRs) embedded insole Image modified from [32].

4 Conclusion and Future Work

This article provided a brief overview of several key components for wearable gait retraining systems. While there are few completely portable systems with wearable sensing and wearable feedback, much research has proven the effectiveness of key components. Combining these various components into a cohesive wearable system could provide gait retraining benefits to a diverse patient population. Furthermore, with the increased connectivity of portable computing devices such smart phones, it may soon be possible to stream movement performance data from the user to a clinical professional in a remote location (Fig. 6), which could potentially expand the expertise of clinical professionals as far as the internet can extend.

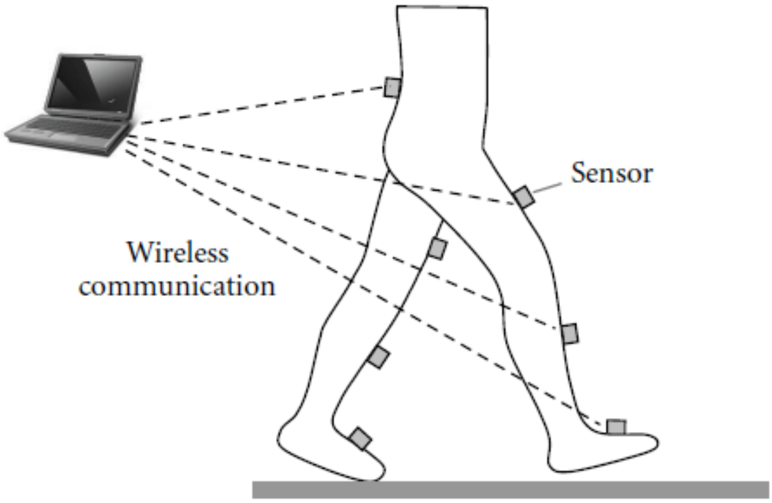

Fig. 6. An array of wireless sensors could potentially be linked to networks for analysis by a clinical professional in a remote location. Image modified from [18].

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