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Review

Quantified self and human movement: A review on the clinical impact of wearable sensing and feedback for gait analysis and intervention

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ABSTRACT

The proliferation of miniaturized electronics has fueled a shift toward wearable sensors and feedback devices for the mass population. Quantified self and other similar movements involving wearable systems have gained recent interest. However, it is unclear what the clinical impact of these enabling technologies is on human gait. The purpose of this review is to assess clinical applications of wearable sensing and feedback for human gait and to identify areas of future research. Four electronic databases were searched to find articles employing wearable sensing or feedback for movements of the foot, ankle, shank, thigh, hip, pelvis, and trunk during gait. We retrieved 76 articles that met the inclusion criteria and identified four common clinical applications: (1) identifying movement disorders, (2) assessing surgical outcomes, (3) improving walking stability, and (4) reducing joint loading. Characteristics of knee and trunk motion were the most frequent gait parameters for both wearable sensing and wearable feedback. Most articles performed testing on healthy subjects, and the most prevalent patient populations were osteoarthritis, vestibular loss, Parkinson's disease, and post-stroke hemiplegia. The most widely used wearable sensors were inertial measurement units (accelerometer and gyroscope packaged together) and goniometers. Haptic (touch) and auditory were the most common feedback sensations. This review highlights the current state of the literature and demonstrates substantial potential clinical benefits of wearable sensing and feedback. Future research should focus on wearable sensing and feedback in patient populations, in natural human environments outside the laboratory such as at home or work, and on continuous, long-term monitoring and intervention.

1. Introduction

The miniaturization of sensing, feedback, and computational devices has opened a new frontier for gait analysis and intervention. Wearable systems are portable and can enable individuals with a variety of movement disorders to benefit from analysis and intervention techniques that have previously been confined to research laboratories and medical clinics. Consumer demand for wearable computational devices such as smart phones has driven down the cost of sensing and actuation components, while simultaneously pushing technological development to enable long-term (hours and days) of continuous use. Thus, there is increasing potential for wearable sensing and feedback systems to provide significant clinical benefits to the broader population.

Increasingly, individuals are joining societal movements such as quantified self [1], life log [2], and Sousveillance [3] and amassing large amounts of personal information through automated wearable systems. In addition, as the distribution of commercial wearable systems, such as Nike + Fuelband, FitBit, Jawbone UP and Google Glass, spreads, societies are moving toward a point where the tracking and feedback of daily information related to walking, working, eating, and sleeping is standard. One aspect of this technological transformation which holds particular interest is that of wearable systems for clinical gait assessment and intervention.

Wearable sensing has long been suggested as a means of measuring human movements [4]. Recent technological advances

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have produced sensors that are smaller, lighter, and more robust than previous versions and are often combined with portable computation devices, such as smartphones, for a variety of applications [5]. The small size and light weight of accelerometers, gyroscopes, and magnetometers make these a convenient and practical choice for mobile measurements, and the combined packaging of accelerometers and gyroscopes in an inertial measurement unit [6] or accelerometers, gyroscopes, and magnetometers in a magnetometer-accelerometer-rate-gyro [7] have further facilitated the ease-of-use. These advances have enabled new opportunities, not previously possible, to utilize technology for human movement analysis and intervention. Simple systems involving a single accelerometer or a foot switch have been used to detect various spatiotemporal parameters such as step count, stride length, cadence, and walking speed [8–11], while more complex systems have been created with arrays of accelerometers, gyroscopes, and magnetometers worn across the body to measure joint and segment kinematics [6,12–14].

While wearable sensing enables gait assessment, wearable feedback facilitates gait intervention. Wearable haptic (touch) feedback has been used to facilitate gait changes in foot progression angle [15], tibia angle [16], and medio-lateral trunk tilt [16–18]. Wearable haptic feedback has also been used to alter knee loading patterns during gait by alerting users of center of pressure values [19] or knee loading measurements [20]. Wearable auditory feedback has been used to improve balance through modifying trunk displacement [21].

Although more and more people are incorporating wearable systems into their daily lives, the clinical applications providing societal benefits of these systems are unclear. We undertook this review to determine the clinical applications of wearable sensing and feedback for human gait assessment and intervention. Analysis of these applications could suggest future research in which wearable systems could benefit society by enhancing mobility, and treating and preventing neuromusculoskeletal disease.

2. Methods

2.1. Literature search strategy

A literature search was performed for articles published through March 6, 2013 using the following databases: Medline (1950-), Science Citation Index Expanded (SCI-EXPANDED) (1900-), Cumulative Index to Nursing and Allied Health Literature (CINAHL) (1981-), and Cochrane Central Register for Controlled Trials (COCHRANE) (1966-). The search focused on retrieving articles that included the following elements: wearable AND gait AND (sensing OR feedback) (see Table 1 for specific search terms). The search was limited to articles published in English and excluded dissertations, theses, conference proceedings, and conference abstracts.

2.2. Inclusion and exclusion criteria

Two reviewers (PBS and WJ) independently reviewed all titles and abstracts of articles retrieved from the databases search. Inclusion/exclusion disagreements were resolved by consensus. The full text was then retrieved and further reviewed for all articles that could not be excluded based on the title and abstract alone.

Articles were included which involved a system with wearable sensing or wearable feedback used to either assess or train human gait. Wearable, or body-worn, was defined as being supported off the ground by the body. Wearable examples could include: an accelerometer strapped to the shoe, headphones worn in the ears, a visual display held in the hand, a vibration motor taped to the body, or a gyroscope in a backpack worn on the back. Wearable sensing and feedback were required to report values of at least one of the following: (1) segment kinematics of the foot, shank, thigh, pelvis, or trunk; (2) joint kinematics of the ankle, knee, or hip; (3) joint moments of the ankle, knee, or hip; or (4) joint forces in the ankle, knee, or hip. Because other articles have reviewed wearable systems for measuring spatiotemporal parameters [8], for physical activity identification [22], and for electromyographic (EMG) measurements [23], we included articles focused on spatiotemporal parameters, physical activity identification, and wearable EMG only when they also targeted at least one of the required gait parameters listed in the previous sentence. Wearable feedback studies were required to alert the user to modify at least one of the gait parameters listed above through one of the five senses: sight, hearing, touch, smell, or taste.

Table 1
Specific search terms used in the systematic literature review. In general the search focused on retrieving articles which involved elements of: wearable AND gait AND (sensing OR feedback). * Indicates wildcard for the rest of the term.

General	Specific search terms
Wearable	portab* OR weara* OR attach* OR strap* OR tape*
	AND
Gait	gait OR walk* OR jog OR run OR runn* OR ambulat* OR locomot*
	AND
Sensing OR feedback	sensin* OR acceler* OR gyro* OR magnatom* OR imu OR feedb* OR biofeedb* OR real-time* OR haptic* OR vibra* OR vibro* OR visual* OR touch* OR audito* OR train* OR retrain* OR altered* OR modific*

Articles were excluded for movement activities other than gait. Articles were excluded that did not involve living human subjects, such as animal studies or human cadaver experiments, as were articles that did not involve primary research. Studies that initiated involuntary gait modifications, such as wearable robotic rehabilitation or powered exoskeletons, were also excluded as this has been the subject of previous review [24]. Bibliographies of articles from the databases search passing the inclusion/exclusion criteria were searched recursively for other potentially eligible articles.

2.3. Data extraction

Two reviewers (PBS and WJ) carefully read and extracted the following data from each included study: study design (sensing, feedback, or both); subject type (e.g. healthy, osteoarthritis, or Parkinson's disease); walking surface (e.g. overground or treadmill); gait parameters (segment orientations, joint kinematics, joint moments, and joint forces); sensor type (e.g. accelerometer or potentiometer); feedback sensation type (e.g. touch or vision).

3. Results

In total, 1344 articles were retrieved from the literature search (Fig. 1). A critical examination of the titles and abstracts using the pre-determined inclusion and exclusion criteria produced 116 remaining articles, and the full text review ultimately yielded 76 articles that satisfied all the inclusion criteria. The publication dates of included articles spanned from 1969 to 2013, and 70% of the articles were published in the last 10 years.

The majority of articles involved testing on healthy subjects alone (Table 2). For articles involving patient populations, osteoarthritis was the most common, followed by vestibular loss, Parkinson's disease, and hemiplegia. Sixty-four articles involved studies with only wearable sensing, 3 articles involved only wearable feedback, and 9 articles involved both wearable sensing and wearable feedback. Studies with only wearable feedback used grounded cameras and marker-based motion capture for sensing [16,19,20]. In most studies, gait trials were performed overground (58 articles). In 8 articles, gait trials were performed on a treadmill, and in 7 articles, trials were performed both overground and on a treadmill. Two studies did not report where gait trials were performed, and one study performed gait trials on a mini-trampoline.

3.1. Sensing for human gait

The most common wearable sensor for measuring gait was the inertial measurement unit (Table 3). An inertial measurement unit, or IMU, is comprised

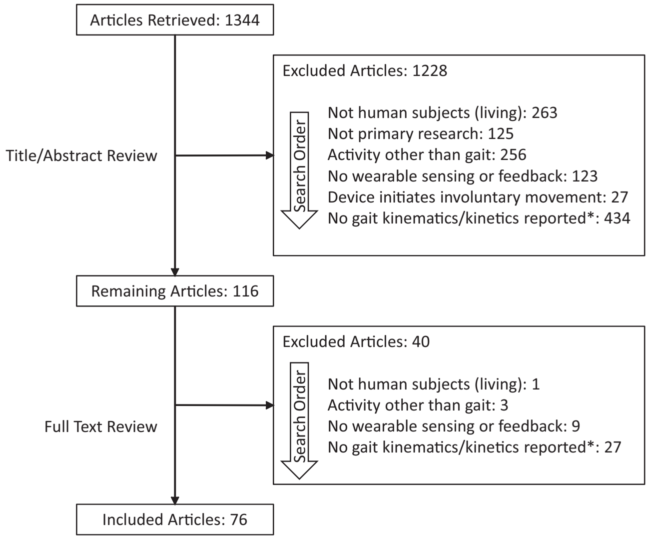

Fig. 1. Flow diagram depicting article selection process. * Specific kinematic and kinetic measurements required for inclusion are described in Section 2.2, paragraph 2.

Table 2
Patient populations. The majority of articles performed testing on healthy subjects alone. For articles involving patient populations, osteoarthritis was the most common. When a given population was reported in more than 10 articles, only the most recent 10 articles were listed.

Subject type	Articles (total – references)
Healthy	48 – [12,13,16,19–21,25–28]
Osteoarthritis	9 – [29–37]
Vestibular loss	4 – [38–41]
Parkinson's disease	3 – [42–44]
Hemiplegia	3 – [45–47]
Multiple sclerosis	2 – [48,49]
Head trauma	2 – [49,50]
Prosthesis	2 – [31,51]
Other[a]	3 – [52–54]

[a] Other: anterior cruciate ligament injury, spinal cord injury, and central nervous system lesions were each reported in a single article.

of a 3-axis accelerometer and a 3-axis gyroscope packaged together and can be used to measure angles, angular velocities, and angular accelerations of a single rigid body or when used in pairs between two rigid bodies in three-dimensional space [6]. Several articles used the magnetic accelerometer rate gyroscope, or MARG, which is an IMU packaged together with a 3-axis magnetometer (e.g. [7]). The most common sensor used in isolation was the goniometer, followed by the accelerometer, gyroscope, and force sensitive resistor (Table 3).

3.1.1. Targeted gait parameters

Fig. 2 depicts the locations of kinematic and kinetic gait parameters targeted for sensing. The knee was the most common location for wearable sensing followed by the trunk and the shank. Several articles also involved wearable sensing for the hip and ankle joints and for the thigh and foot segments. Kinematics and kinetics were most commonly measured about the medio-lateral axis for the trunk, hip, knee, ankle, thigh, and shank. Gait applications were generally for walking in straight lines, though there were other applications such as for running [25].

Studies that report kinematic (angle, angular velocity, and angular acceleration) and kinetic (force and moment) gait parameters of each joint and segment for wearable sensing are listed in Table 4. For wearable sensing, gait parameters were often reported about all three axes within a given joint or segment. This may be due to the nature of the sensing package where all three axes were usually available.

3.1.2. Applications

Two primary applications were identified for wearable sensing: *identifying movement disorders* and *assessing surgical outcomes* (see following paragraphs). Other wearable sensing articles were often written as validation studies for a particular sensor system [30,61] or to quantify the repeatability of sensor placement and kinematic measurements over multiple sessions [33]. Other studies focused on the presentation of novel algorithms for accurately measuring

Table 3
Sensor types used for wearable sensing. When a given sensor type was reported in more than 10 articles, only the most recent 10 articles were listed.

Sensor type	Articles (total – references)
Inertial measurement unit	33 – [12,13,25,27,30,42,45,47,48,51]
Goniometer	24 – [26,28,33,36,37,49,55–58]
Accelerometer	11 – [28,44,53,58–64]
Gyroscope	9 – [17,18,21,29,40–42,44,53]
Magnetic accelerometer rate gyroscope	7 – [7,25,27,45,65–67]
Force sensitive resistor	2 – [43,53]
Other[a]	6 – [43,68,69]

[a] Other: polyvinylidene fluoride strips, bend sensors, electric field sensor, miniature load cell, and portable magnetic tracker were each reported in a single article.

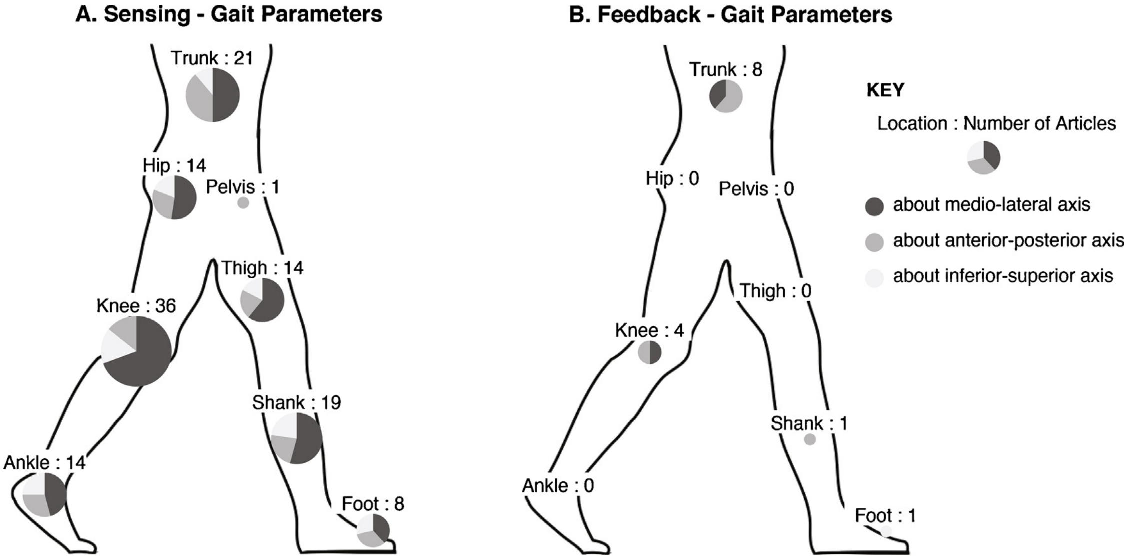

Fig. 2. Target gait parameter locations for (A) wearable sensing and (B) wearable feedback. The number of articles reporting gait parameter locations is indicated at each respective location. The diameter of each pie chart is proportional to the number of published articles reporting that gait parameter location. The relative proportion of kinematic and kinetic parameters about each of the three anatomical axes is indicated in the pie charts. See Tables 4 and 6 for specific gait parameters (i.e. angle, angular velocity, angular acceleration, force, and moment) and their accompanying references. The knee and trunk were most commonly targeted for both sensing and feedback. There are noticeably fewer articles involving feedback than sensing.

Table 4

Wearable sensing. Summary of articles reporting specific kinematic and kinetic gait parameters for wearable sensing. When a given gait parameter was reported in more than 10 articles, only the most recent 10 articles were listed.

Gait parameters	Wearable sensing articles
JOINTS	
Ankle	
About medio-lateral axis	
Angle	[13,28,30,49,58,65,67,70–72]
Angular velocity	[58,69]
Force	[69]
Moment	[69]
About anterior-posterior axis	
Angle	[30,65,67,71–73]
Angular velocity	[69]
Force	[69]
Moment	[69]
About inferior-superior axis	
Angle	[30,65,67,71,72]
Angular velocity	[69]
Force	[69]
Moment	[69]
Knee	
About medio-lateral axis	
Angle	[12,13,26–29,45,47,51,74]
Angular velocity	[51,58]
Moment	[75]
About anterior-posterior axis	
Angle	[27,29,52,65,71,76,77]
About inferior-superior axis	
Angle	[27,29,52,65,71,76–78]
Hip	
About medio-lateral axis	
Angle	[12,13,34,56,62,63,65,71,74,79]
Force	[61]
Moment	[61]
About anterior-posterior axis	
Angle	[12,65,71,79]
Force	[61]
Moment	[80]
About inferior-superior axis	
Angle	[65,71,79]
Force	[61]
SEGMENTS	
Foot	
About medio-lateral axis	
Angle	[30,43,45,70]
Angular velocity	[43,66,69,81,82]
Angular acceleration	[82]
About anterior-posterior axis	
Angle	[30,70]
Angular velocity	[43,66,69,81,82]
Angular acceleration	[82]
About inferior-superior axis	
Angle	[30]
Angular velocity	[43,66,69,81,82]
Angular acceleration	[82]
Shank	
About medio-lateral axis	
Angle	[6,25,30,31,46–48,51,83,84]
Angular velocity	[4,6,53,64,66,69,81,82,85]
Angular acceleration	[6,75,82]
About anterior-posterior axis	
Angle	[30,48]
Angular velocity	[64,66,69,81,82,84]
Angular acceleration	[82]
About inferior-superior axis	
Angle	[30,48]
Angular velocity	[64,66,69,81,82,84]
Angular acceleration	[82]
Thigh	
About medio-lateral axis	
Angle	[7,29,31,46,47,51,53,59,83,84]
Angular velocity	[25,53,85]
Angular acceleration	[75,82]
About anterior-posterior axis	
Angle	[7,29,59]
Angular velocity	[85]
Angular acceleration	[82]
About inferior-superior axis	
Angle	[7,29]
Angular velocity	[85]
Angular acceleration	[82]
Pelvis	
About anterior-posterior axis	
Angle	[32]
Trunk	
About medio-lateral axis	
Angle	[7,17,18,21,25,42,47,48,56,86]
Angular velocity	[18,40–42,44,87]
Angular acceleration	[87]
About anterior-posterior axis	
Angle	[7,17,18,21,32,38,39,42,48,86]
Angular velocity	[18,38,40–42,44,87]
About inferior-superior axis	
Angle	[7,48,60,87]
Angular velocity	[87]

kinematics such as a generalized regression networks algorithm or a sensor fusion algorithm [76,81]. The assessment of a particular wearable sensing system or novel algorithm was frequently performed as a comparison of the same measurements through marker-based motion capture [32]. For the vast majority of these studies testing was performed in a laboratory setting as opposed to testing in natural human environments.

3.1.2.1. Identifying movement disorders. Several studies utilized wearable sensing to identify kinematic differences during gait for patient populations in comparison with asymptomatic controls. Wearable gyroscopes and accelerometers were used to detect differences in trunk sway angles between individuals with multiple sclerosis and controls [48] and between individuals with Parkinson's disease and controls [44]. Goniometers were used to determine ankle dorsi- and plantar-flexion differences between neurologically impaired subjects and controls [49] and an inertial measurement unit was used to determine sagittal, coronal, and transverse ankle kinematic differences between individuals with ankle osteoarthritis and controls [30]. These findings are consistent with the expected differences seen clinically, and support the validation of these devices. Finally, inertial measurement units were used to detect knee flexion/extension and foot angle differences between subjects with hemiplegia and healthy controls [45] and to determine whether hip arthroplasty patients walked with compensatory trunk sway movements [32]. Such applications of wearable sensing could facilitate early detection of these and other gait-related disorders.

3.1.2.2. Assessing surgical outcomes. Another common theme was using wearable sensing to assess the outcome of surgical procedures. Some research groups used flexible electrogoniometry to quantify hip and knee flexion/extension differences before and after total knee replacement surgery [35]. One study employed wearable inertial measurement units on the shank and thigh to quantify 3-dimensional kinematic differences before and after anterior cruciate ligament reconstruction surgery [52]. In another study, body-fixed sensors were used to compare pelvic and trunk kinematics for two different approaches to total hip arthroplasty at 6 weeks, 3 months, and 6 months postoperatively [88]. Wearable sensing has also been used to detect differences in human kinematics for dissimilar total knee replacement prosthetic implants, such as flexible goniometry sensing for standard and high-flexion implants [36] and implants with and without patella resurfacing [37], and angular rate gyroscope sensing for fixed bearing and mobile bearing implants [51], suggesting that wearable sensing offers a convenient way to assess movement-related aspects of surgical outcomes without the need for a marker-based motion capture laboratory.

3.2. Feedback for human gait

Touch was the most common human sensation used to convey feedback information (Table 5). Haptic sensations were primarily given through high-frequency vibration, though one study also used wearable skin stretch [16]. In some studies, haptic feedback was applied at the joint or segment of desired change, such as at the foot, tibia, or trunk to inform foot progression angle, tibia angle, and trunk tilt, respectively [16,86]. In other studies, haptic feedback was applied at different body locations away from the joint or segment of desired change such as on the head for trunk tilt training [21] and on the forearm for knee loading reduction training [20]. It seems that applying haptic feedback on the body either at or away from the desired gait parameter to change can be effective for gait retraining. This finding has important clinical implications in situations where the "target" joint or segment is associated with impaired sensation due to swelling or pain. Training

Table 5
Feedback sensation types used for wearable feedback.

Feedback type	Articles (total – references)
Touch	10 – [16–21,38,39,42,86]
Audio	5 – [17,18,21,50,54]
Visual	3 – [17,18,21]
Taste	0
Smell	0

subjects to change multiple gait parameters simultaneously is much more difficult than training them to change a single parameter as evidenced by a study comparing haptic gait retraining with three simultaneous versus a single gait parameter [89]. There may be an upper limit on the number of gait parameters that can be changed simultaneously, and it is likely that when subjects are presented with too many feedback channels of information, they will simply focus on a manageable number, ignoring the rest [89]. In addition to touch sensations, audio and visual feedback have been successfully used to inform desired movement changes [17,18,21]. No studies involved taste or smell sensations to provide gait feedback (Table 5).

3.2.1. *Targeted gait parameters*

Wearable feedback studies primarily involved the trunk or knee (Fig. 2). Shank and foot wearable feedback were also reported, while no articles involved wearable feedback for the hip, ankle, pelvis, or thigh. Wearable feedback about the anterior–posterior axis and medio-lateral axis were the two most common axes for the trunk and knee. All of the wearable feedback articles targeted kinematic parameters except two [19,20], which targeted kinetic parameters (Table 6). For all articles, the knee moment about the anterior–posterior axis was the only targeted feedback parameter that was not also a targeted sensing parameter.

3.2.2. *Applications*

Two primary applications were identified for wearable feedback: *improving walking stability* and *reducing joint loading* (see following paragraphs). For the vast majority of these studies testing was performed in a laboratory setting as opposed to testing in natural human environments.

3.2.2.1. Improving walking stability. Wearable feedback is effective for gait retraining to improve walking stability by reducing excessive trunk sway movements. In one system, a vest with embedded vibrotactors is worn around the torso and the vibrotactors vibrate to alert users of excessive trunk sway. This has been used to reduce trunk sway in healthy elderly adults [86] and in individuals with vestibular loss [39]. Though not explicitly used for improving stability, vibrotactors have similarly been taped directly to the upper back and vibrated to inform individuals with knee osteoarthritis to increase or decrease trunk sway [90], and wearable rotational skin stretch has been applied to the lower back to inform trunk sway movements in healthy subjects [16].

Another approach to train trunk sway movements to improve stability is through a wearable visor system with visual, auditory, and haptic feedback capabilities [18]. The device has eight vibrotactors on the inside of the visor in contact with the head to give haptic feedback. Two auditory bone conductors oscillate against the mastoid perturbing cochlea hair cell receptors for audio feedback and three light emitting transistors on the bill of the vision flash on and off to provide visual feedback. This system has been used to reduce trunk sway in young and elderly healthy subjects [17,21] and in individuals with Parkinson's disease [42]. The effectiveness of these studies suggests that other patient populations prone to instability and falls due to excessive postural sway could similarly benefit from such systems.

Table 6
Wearable feedback. Summary of articles reporting specific kinematic and kinetic gait parameters for wearable feedback.

Gait parameters	Wearable feedback articles
JOINTS	
Ankle	
About medio-lateral axis	
Angle	[54,72]
Knee	
About anterior-posterior axis	
Moment	[19,20]
SEGMENTS	
Foot	
About inferior-superior axis	
Angle	[16]
Shank	
About anterior-posterior axis	
Angle	[16]
Trunk	
About medio-lateral axis	
Angle	[17,18,21,42,86]
About anterior-posterior axis	
Angle	[16–18,21,38,39,42,86]
Angular velocity	[38]

3.2.2.2. Reducing joint loading. Wearable feedback has been used to retrain gait to reduce joint loads, especially for applications in knee osteoarthritis. Toe-in gait [15] has been trained with wearable haptic feedback to reduce the knee adduction moment, a measure associated with medial compartment knee osteoarthritis [91]. Additionally, when wearable haptic feedback was used to train toe-in gait over six weeks, individuals with medial compartment knee osteoarthritis reported less knee pain and greater function post-training and at the one-month follow-up [90]. Wearable haptic feedback has also been used to reduce the knee adduction moment by informing a medial shift of the center of pressure [19], altering the tibia angle [16], or increasing lateral trunk sway [16]. Wearable haptic feedback has also been used to present direct feedback of the knee adduction moment, giving subjects the freedom to choose kinematic gait changes to reduce the knee adduction moment [20]. Finally, wearable auditory feedback has been used to reduce the knee joint rate of loading and increase the knee flexion angle during walking [92].

4. Discussion

The purpose of this review was to assess clinical applications of wearable sensing and feedback for human gait and to identify areas of future research. Four themes emerged, namely the use of wearable systems for: identifying movement disorders; assessing surgical outcomes; improving walking stability; and reducing joint loading. Wearable systems research to date has focused more on analysis and less on intervention as only a small fraction of the articles involved wearable feedback (Fig. 2). Lastly, much of the research effort to date has been focused on healthy subjects. Based on this review, it seems that wearable sensing systems are available and shifting the research focus to patient populations could bring greater societal benefits by improving mobility and treating/preventing neuromusculoskeletal disease.

It appears that quantified self and other similar movements [1–3] hold potential to significantly benefit society. While in the broader scope of our Internet of Things society, lasting impact generally comes through, "data creation, information generation, meaning-making, and action-taking" [1]. Wearable systems movements like quantified self have typically focused on the data creation and information generation aspects through prolonged self-monitoring without explicitly promoting how self-data should be applied. In this review, it is clear there are concrete applications of wearable systems which fall under the meaning-making and action-taking categories. While these are specific to gait, there are likely other related clinical applications of wearable systems outside of this scope.

Wearable sensing, when used for a single movement axis, was most frequently performed about the medio-lateral axis of each joint or segment. This was most apparent for the knee joint, where knee flexion/extension was reported roughly four times more frequently than either knee abduction/adduction or knee internal/external rotation (Fig. 2). Similarly, for the hip and ankle joints, flexion/extension was most commonly reported. Assuming constant noise about all axes, since the range of human gait movements out of the sagittal plane is small, the signal-to-noise ratio is lower than in the sagittal plane, making the collection of accurate measurements in the frontal and transverse planes less accurate. Also, inertial measurement units, the most commonly used wearable sensors, rely on the acceleration of gravity vector for increased accuracy [6]. Thus measurements primarily in the transverse plane are less accurate and can only be measured as changes in relative angle, not absolute angle. While wearable sensing was occasionally used to estimate gait kinetics, such as foot transducers and inertial sensors to estimate ankle joint moments [69] or accelerometry to estimate hip forces and moments [61], the vast majority of wearable sensing studies involved only kinematics sensing (Table 4).

Few studies used wearable feedback for gait retraining. Many real-time biofeedback studies have been performed in laboratories with grounded equipment, demonstrating the clinical benefits of real-time gait retraining such as: changes in trunk, hip, knee, and foot kinematics to alter knee joint loading for medial compartment knee osteoarthritis [16,20,90,93,94]; reducing lower extremity loads during running to prevent tibial stress fractures [95]; and gait symmetry retraining for individuals post-total hip replacement [96]. This review shows that the benefits of real-time biofeedback for gait retraining through wearable feedback devices are underutilized; evidenced by the fact that no articles reported wearable feedback for training the hip, pelvis, thigh, or ankle (Fig. 2). Wearable systems have the potential to extend the benefits demonstrated in laboratory biofeedback studies to a broader population. This is particularly true for applications requiring multiple training sessions spread out over weeks or months. In a recent study, weekly gait retraining sessions spread over 6 weeks to train toe-in walking gait enabled individuals with knee osteoarthritis to walk with lower medial compartment loading and less knee pain [90]. If shown to be maintained over the longer-term, gait retraining to reduce knee joint loading has implications for the long-term management of the disease as well as the economic impact of knee osteoarthritis. Similarly, weekly gait retraining sessions using wearable feedback have enabled athletes to run with less tibial shock, thus lowering the chance of tibial stress fractures [95]. Interventions like these requiring multiple training sessions become more practical with a wearable gait retraining system that subjects can bring home and use on their own when compared to stationary motion capture systems confined to a laboratory setting.

A majority of studies with wearable systems performed testing only on healthy subjects (Table 2). Many wearable systems are in the early stages of development and are first being tested in proof-of-concept studies on healthy subjects. This has been the case for real-time biofeedback gait retraining studies to reduce medial compartment knee loading. Early proof-of-concept studies were performed on healthy subjects [16,20,94], with subsequent studies conducted with individuals diagnosed with knee osteoarthritis [15,90,97]. Healthy individuals are often easier to recruit, and it may be easier for them to use wearable systems than some patient populations. For example, it would likely be easier for a healthy subject to use a wearable system to retrain reduced trunk sway movements to increase stability during gait than for an individual with Parkinson's disease. If it is true that the healthy subject testing for wearable systems is primarily conducted as a proof-of-concept, then it is likely that more research will be performed using wearable systems on patient populations in the future.

There are tradeoffs amongst the different types of wearable sensors to estimate gait parameters. Accelerometers and gyroscopes sense accelerations and angular velocities, which when integrated to compute positions and orientations are prone to integrated noise and drift errors [53]. Magnetometers sense the strongest magnetic field, which is generally toward the north pole, an absolute direction, but are subject to signal distortion from local magnetic fields. Goniometers, on the other hand, are immune to drift errors and magnetic field distortion, directly sensing joint angles [26]. However, goniometers can be bulky, particularly when measuring multiple joints in three-dimensional space, and they are prone to inaccuracies because they are sensitive to precise attachment on the body. Thus goniometers may be less practical when compared with inertial sensors.

Wearable sensing is typically accurate to within a few degrees. Three-axis gyroscopes on the shank and thigh used to compute three-dimensional knee joint angles have produced root-mean-square (RMS) errors of approximately 2–4° [52]. Similarly, errors for IMU systems measuring foot, ankle, knee, and hip kinematics are typically 2–5° [13,30]. These research findings align with commercial manufacturing specifications which have reported IMU roll/pitch/yaw dynamic orientation errors at 2° or 3° (Xsens, www.xsens.com; APDM, www.apdm.com). Wearable electrogoniometers typically report joint errors of 3–4° during gait [26]. Neural networks have been used to reduce measurement errors for wearable systems, though effectiveness decreases when applied to subjects outside the training set [81].

While most studies in this review were performed inside a laboratory, there are notable exceptions. Motoi et al. [46] used three inertial measurement units to monitor sitting and standing posture and trunk, thigh, and calf sagittal plane kinematics during daily activities at home and in a clinic for individuals undergoing rehabilitation. In Huddleston et al. [57], electrogoniometers and accelerometers were used to track knee flexion/extension angles throughout the normal work day. Knee motion was assessed during a variety of work activities including: performing a surgical operation, seeing patients in a clinic, working at a computer desk, and transporting clients to view residential property. Strohrmann et al. [25] assessed running kinematics via 12 accelerometer–gyroscope–magnetometer units while subjects ran outside on a track. Finally, Cardon et al. [60] tracked sitting and walking posture with an accelerometer as children moved from classroom to classroom in a school throughout the day. Though studies with wearable systems are still primarily conducted in laboratories, these examples show the feasibility and potential for use in daily living.

No studies involved taste or smell, though there is no reason to believe that creative future research could not involve these sensing modalities for gait retraining. For example, tongue stimulation has previously been used to increase postural standing stability [98]. While visual and audio feedback have been more commonly used than touch feedback in grounded laboratory biofeedback gait studies (see [99] for a review), it may be that normal ambulation outside the laboratory is more demanding for visual and auditory input, and less so for haptic sensation. For example, walking down a busy sidewalk requires constant visual attention, and adding visual feedback for gait retraining may overburden the visual input stream. However, haptic feedback may be more appropriate in that skin sensation would not be relied upon as heavily in the same walking task. In addition, visual feedback is commonly used and is effective for biofeedback training [94,99]; however, it is usually performed via a stationary screen in a laboratory and is thus not wearable, though recent technological efforts such as Google Glass are seeking to change this. Still, as normal, overground gait outside a laboratory is a visually intensive task, visual feedback in these situations may add cognitive burden [100].

While this review focused on kinematic and kinetic parameters for human gait, there are other human movement activities and gait parameters outside the scope of this review that could also benefit from wearable sensing and feedback for assessment and intervention. For example, wearable accelerometers and gyroscopes have been used to measure spatiotemporal parameters [8] and to measure, classify, and assess human physical activity [22]. Similarly, there are other non-gait human movements that could benefit from wearable sensing and feedback. Standing postural balance is one example in which wearable systems have been used to improve stability for the elderly [101] and for individuals with vestibular deficits [102]. Wearable systems have also been used to assist in a variety of human learning tasks such as drumming [103], snowboarding [104], and jump landings [105]. Most wearable system movement retraining studies of this type have been published in the last few years, and it is thus plausible that the growth of wearable systems will extend into a diverse array of human movement applications.

5. Future work

Wearable systems offer an inherent advantage over grounded laboratory equipment; they are portable and can thus be used outside of the laboratory in humans' natural environment. Laboratory experiments are beneficial in that they are typically well-controlled, but they may not always be able to recreate real-life scenarios. For example, Strohrmann et al. [25] used wearable sensing to assess the kinematic effects of fatigue in runners on a treadmill in a laboratory and on an outdoor track. They found that observations from treadmill running cannot always be applied to outdoor running. Furthermore, practical realities limit the amount of time subjects can spend testing in a laboratory, while wearable systems can in theory be worn continuously throughout the day for months or even years. This continuous monitoring is at the heart of the Quantified Self movement since it will likely give a more accurate picture of human motion realities than short periods of laboratory testing. Utilizing wearable systems for continuous, long-term usage could enable gait assessments and interventions not previously possible. In conclusion, this review shows the clinical impact of wearable sensing and feedback to date and points to future research possibilities particularly for patient populations, in natural environments, and for long-term, continuous use.

Authors' contribution

All authors have made substantial contributions to the following: (1) the conception and design of the study, or acquisition of data, or analysis and interpretation of data, (2) drafting the article or revising it critically for important intellectual content, (3) final approval of the version to be submitted. Each of the authors has read and concurs with the content in the manuscript. The manuscript and the material within have not been and will not be submitted for publication elsewhere.

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Conflict of interest

None of the authors had any conflict of interest regarding this manuscript.

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