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Wearable technology mediated biofeedback to modulate spine motor control: a scoping review

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Abstract

Background Lower back pain (LBP) is a disability that affects a large proportion of the population and treatment for this condition has been shifting towards a more individualized, patient-centered approach. There has been a recent uptake in the utilization and implementation of wearable sensors that can administer biofeedback in various industrial, clinical, and performance-based settings. Despite this, there is a strong need to investigate how wearable sensors can be used in a sensorimotor (re)training approach, including how sensory biofeedback from wearable sensors can be used to improve measures of spinal motor control and proprioception.

Research question The purpose of this scoping review was to examine the wide range of wearable sensor-mediated biofeedback frameworks currently being utilized to enhance spine posture and motor function.

Methods A comprehensive scoping review was conducted in adherence with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Guidelines extension for Scoping Reviews (PRISMA-ScR) across the following databases: Embase, PubMed, Scopus, Cochrane, and IEEEXplore. Articles related to wearable biofeedback and spine movement were reviewed dated from 1980 - 2020. Extracted data was collected as per a predetermined checklist including the type, timing, trigger, location, and magnitude of sensory feedback being applied to the body.

Results A total of 23 articles were reviewed and analysed. The most used wearable sensor to inform biofeedback were inertial measurement units (IMUs). Haptic (vibrotactile) feedback was the most common sensory stimulus. Most studies used an instantaneous online trigger to initiate sensory feedback derived from information pertaining to gross lumbar angles or the absolute orientations of the thorax or pelvis.

Conclusions This is the first study to review wearable sensor-derived sensory biofeedback to modulate spine motor control. Although the type of wearable sensor and feedback were common, this study highlights the lack of consensus regarding the timing and structure of sensory feedback, suggesting the need to optimize any sensory feedback to a specific use case. The findings from this study help to improve the understanding surrounding the ecological utility of wearable sensor-mediated biofeedback in industrial, clinical, and performance settings to enhance the sensorimotor control of the lumbar spine.

Keywords Wearable technology, Kinematics, Sensory biofeedback, Spine movement, Spine posture

Background

Low back pain (LBP) is the leading cause of lived-with disability and is the most common musculoskeletal dysfunction globally [14, 41]. Further, LBP is the leading cause of activity limitation [41], dramatically limiting

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one's quality of life. Despite the major global public issue LBP continues to pose, there remains limited understanding about the underlying pathologies that may contribute to the development and persistence of LBP. Non-specific LBP (NSLBP) does not have any underlying structural basis, or prevailing treatment option. NSLBP is thought to be multifaceted in nature, with different underlying mechanisms that can be psychosocial and mechanical [25, 27]. In general, a biopsychosocial model of chronic LBP is widely accepted, with a specific emphasis on the implementation of the biomechanics of the disorder [9], however, there still lacks evidence for specific motor impairments leading to spine and trunk related motor dysfunction. Previous research surrounding LBP has focused on the neuromuscular deficiencies in individuals suffering from LBP, and suggested the presence of varying typologies (i.e., maladaptations) implemented by the motor control system in response to chronic LBP states [37]. These hypothetical typologies (i.e., subgroups) include a broad range of motor control phenotypes. For example, in one hypothetical scenario, some individuals may have a tendency to co-activate their trunk musculature as a pain avoidance mechanism to enhance spinal stiffness (i.e., mechanical stability). In contrast, others may adapt altered motor control strategies in response to sensory deficits (i.e., reduced spine/trunk proprioception) without adopting a spine stiffening strategy [37]. LBP patients demonstrate reduced spatial tactile acuity [18], a decreased ability to detect changes in trunk position and significantly higher trunk flexion repositioning error (i.e., both passive and active repositioning) compared to healthy individuals [17, 24]. Additionally, balance deficits have been exhibited in the LBP population compared to healthy controls, especially when asked to perform balance tasks with their eyes closed, further indicating impaired proprioception and increased reliance on visual feedback [10, 19, 20, 22]. Given the impaired motor control present with those experiencing LBP [13], emphasis on therapies leveraging sensorimotor learning principles have begun to emerge. Such approaches rely on the delivery of targeted sensory feedback to enhance motor learning and proprioceptive awareness.

Spine posture and movement have historically been monitored using optical motion capture systems that use physical kinematic markers which can be affixed to the skin, or rigid bodies to represent underlying bony landmarks. These optical kinematic systems can be cumbersome and have limited utility in a clinical setting due to factors such as the cost, time, and training required to ensure proper function. Additionally, the use of these optical systems typically requires extensive anatomical knowledge, thereby dramatically limiting the ecological utility of such systems to a broad spectrum of consumers. In part due to these limitations of lab-based motion capture, there has been a recent uptake in the use of wearable sensors to facilitate the tracking of human kinematic variables in real-world (i.e., clinical) settings. Simpson et al. [34] reported that wearable sensors have good accuracy for assessing spinal posture. Further, according to systematic reviews done by Simpson et al. [34] and Papi et al. [27], inertial measurement units (IMUs) are the most common type of wearable sensor used to monitor spine movement. In addition to monitoring spine movement, IMUs have been paired with mobile-based applications to provide systematic biofeedback to the user to allow them to adjust their posture and/or movement patterns [33], and therefore present as a potential means to enhance sensorimotor training paradigms.

Considerations during the administration of sensory feedback to enhance motor outcomes are the type, timing, trigger, location, and magnitude of sensory feedback being applied to an individual. There are different modalities of biofeedback that can be administered such as visual, auditory, and haptic (i.e., tactile). Further, the timing of any biofeedback can be presented to the user in real-time (concurrent/online) while the movement or posture is occurring, or later (terminal/offline) once a bout of activities is completed [33]. In addition, concurrent/online biofeedback can be implemented in an instantaneous, or continuous manner whereby feedback is triggered based on a pre-defined threshold (instantaneous) or throughout the entirety of a movement (continuous). The triggering of any instantaneous or continuous biofeedback can be referenced to a variety of underlying kinematic phenomena including absolute segment orientation or set target joint angles. Finally, the location and magnitude of any sensory cue, as well as recording equipment, can be varied to further optimize motor learning outcomes. Collectively, there is a lack of consensus on the administration of these variables to optimize motor learning related to spine posture and movement.

Due to the ease of acquisition with wearable sensors to monitor spine posture and movement, wearable sensor-mediated biofeedback can be easily introduced in both clinical and real-world settings for everyday use. Given the wide variety of biofeedback types and timing, there is a clear need to optimize biofeedback administered by a wearable sensor to allow users to refine motor strategies based on reliable kinematic data streams. This is particularly relevant given that the type and timing of any wearable sensor-mediated biofeedback may vary across different use cases (i.e., wearable sensor-mediated biofeedback used to alert users to sustained high-risk postures vs. biofeedback implemented in a training framework to enhance user proprioception). As such, the purpose of this scoping review was to examine the wide range of wearable sensor-mediated biofeedback frameworks currently being utilized to enhance spine posture and motor function. Specific biological outcome measures relating to how any wearable sensor-mediated biofeedback can improve or alter clinically relevant outcomes (e.g., spine posture or range of motion) were explored. The findings of this scoping review aim to synthesize data across multiple scientific domains (engineering, computer science, neuroscience, rehabilitation medicine) that are using wearable sensor-mediated biofeedback to improve spine motor function.

Methods

To facilitate this review, databases were queried between the months of August 2020 and September 2020.

Search strategy

Five databases were searched including Embase, PubMed, Scopus, Cochrane, and IEEEXplore. Relevant spelling variations, synonyms, and alternative terms were included and modified as deemed appropriate by the researchers for each database. Sensors, outcomes, biofeedback, and spine were used as general areas to identify a comprehensive list of articles that encompassed the scope of this review, and the specific search terms for each can be found in Table 1. The reference lists of relevant articles were screened for appropriate titles that may have been missed in the electronic searches. Search results from each database were exported in an ASCII format and compiled using Microsoft Excel for further review and removal of duplicates. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines were followed, and the review process is summarized in Fig. 1.

Inclusion and exclusion criteria

Articles were included if they were published in English, assessed the spine/trunk, used wearable (wireless) technologies, implemented sensory biofeedback, were peer-reviewed, involved an adult population (>18 y/o), presented original data, and were published on or after 1980. Articles were excluded if they were a review, pilot or case-study (i.e., insufficient sample size where n<5), book or book chapter, used non-wearable devices, described potential technologies not validated on human subjects, did not assess motion of the spine/trunk, or featured wearable technologies that are classified as robotic or exoskeletons.

Selection process

Duplicate studies were removed and a primary screening of titles retrieved from each database was completed by one reviewer (AB). Following the primary screening, abstracts of potential articles were assessed by one reviewer (AB) with secondary assessment by a second reviewer if necessary (JPN). Following the title and abstract triage, two reviewers (AB and JPN) reviewed the full-text of potential articles against the eligibility criteria to ensure the articles satisfied the requirements for this scoping review.

Quality appraisal and data extraction

The overall quality of the articles was rated using adapted quality appraisal criterion derived from Papi et al. [27] and Ratcliffe et al. [29]. Each form was used to assess the quality of articles based on items such as external validity, potential outcome biases, and protocol reporting, specifically evaluating outcome evaluation and use of the technologies. The quality appraisal checklist has 20 items (Table 2); each item is rated as zero (no detail or comment), one (limited detail) or two (good detail). Articles were evaluated and scored based on the combined quality appraisal checklist by two reviewers (AB and JPN), and any discrepancies on scores (>1 point separation between reviewers) were settled by a third reviewer (SMB). Mean results are reported throughout the paper, unless otherwise noted.

Further to the quality appraisal, a customized data extraction form was developed to identify relevant points

Table 1 Search terms used

General Area	Specific Search Terms
Sensors	Sensor **OR** inertia **OR** accelerometer **OR** gyroscope **OR** goniometer **OR** wearable **OR** portable **OR** movable **OR** worn **OR** ambulatory **OR** non-invasive **OR** wireless **AND**
Outcomes	kinetic **OR** kinematic **OR** motion **OR** movement **OR** assessment **OR** joint **OR** frontal **OR** sagittal **OR** transverse **OR** twist **OR** flexion **OR** extension **OR** lateral bending **AND**
Biofeedback	biofeedback **OR** feedback **OR** sensory **OR** tactile **OR** vibration **OR** touch **OR** haptic **OR** auditory **OR** sound **OR** visual **OR** sensorimotor **AND**
Spine	Spine **OR** spinal **OR** back **OR** vertebra

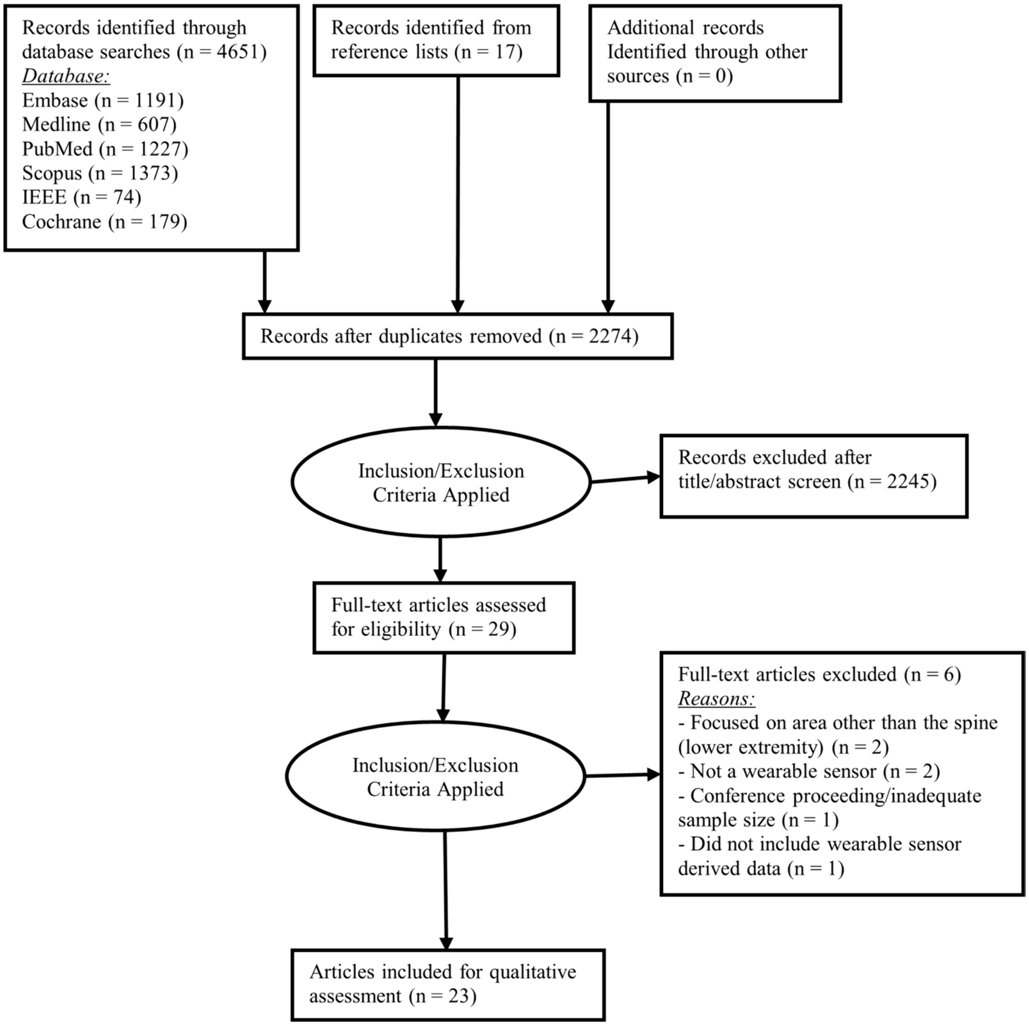

Fig. 1 PRISMA chart outlining the review process

for each full-text included for review. These key relevant points included study aims and design, sample size and population, wearable sensor type and instrumentation, kinematic data obtained, biofeedback type, biofeedback thresholds and triggers, conclusions, and limitations. Data extraction was completed by two researchers (AB and HM) in consultation with a third reviewer (SMB). Relevant data were summarized in a tabular format, and further interpreted to identify any systematic trends present throughout the reviewed literature.

Results

Article selection

The search identified 4651 potentially relevant articles, with 17 articles identified from the references of related articles. 2274 articles remained for consideration after duplicates were removed. Following the screening of titles and abstracts for inclusion and exclusion criteria, 29 articles were retrieved for further full-text review. Six additional full-text articles were then excluded due to the lack of association with the spine ($n=2$), or the lack of wearable sensor data ($n=3$), and inadequate sample size ($n=1$). The final number of articles included for full review was 23. The article selection process and justifications for full-text exclusion are shown in Fig. 1.

Quality of reviewed articles

Of the 23 articles selected for full review, one paper was rated at low quality, 13 were rated at medium quality, and nine were rated at high quality. Itemized scores for each paper are presented in Table 3. Across most papers, sample sizes were poorly justified, as demonstrated by low scoring for a majority (16/23) of papers on item six. Further, 10/23 studies included demonstrated average or below average reporting on both standardization of spine/trunk movement instructions, and signal handling

Table 2 Quality appraisal questions

QUALITY INDEX ITEM
1. Were the research objectives or aims clearly stated?
2. Was the study design clearly described?
3. Was the study population adequately described?
4. Were the eligibility criteria specified?
5. Was the sampling methodology appropriately described?
6. Was the sample size justified?
7. Did the method description enable accurate replication of the measurement procedures?
8. Was the participants' assessor described (e.g., expertise)?
9. Was a system for standardizing movement instructions reported?
10. Was equipment design and setup clearly described?
11. Were sensor locations accurately and clearly described?
12. Was the sensor attachment method clearly described?
13. Were the spine segments analyzed clearly described?
14. Was the signal/data handling described?
15. Were the main outcomes measured, and the related calculations (if applicable) clearly described?
16. Was the type of biofeedback clearly described?
17. Was the participant instructed how to respond to the biofeedback?
18. Were the main findings of the study stated?
19. Were the statistical tests appropriate?
20. Were the limitations of the study clearly described?

and processing (14/23). In contrast, most studies were rated as high quality on reporting the main objectives of the research (14/23), main findings of the research (21/23) and appropriate statistical tests used (18/23). Perhaps most important to the objectives of the current scoping review, almost all studies reported high detail regarding the type (20/23) and implementation of biofeedback (16/23).

Descriptive aspects of reviewed articles

Of the articles reviewed, 10/23 examined a healthy participant population, free of any neuromuscular or musculoskeletal disorders related to spine/trunk. In contrast, 9/23 articles reported a clinical population, including patients with LBP, Parkinson's disease, or other vestibular deficits. Two articles [1, 42] assessed both a healthy and a clinical population and two [7, 35] did not report any specific participant demographics, instead referring to them as "users" (Table 4).

The majority (21/23) of the articles reviewed utilized inertial sensors (i.e., IMUs, accelerometers, gyroscopes), with one study [15] also incorporating EMG data. One article [26] assessed posture through a strain-based sensor affixed to the trunk dorsum. Finally, one article reported use of a wearable postural stabilizer [39], but failed to provide adequate information regarding the sensor type and function.

The primary outcome of 8/23 articles focused on joint angles (i.e., lumbar spine, hip, neck), while 14/23 articles reported on segment orientations (i.e., body tilt relating to the thorax and pelvis orientation relative to gravity, postural control). Further, 1/23 articles included outcomes related to muscle activation through EMG [15], and 1/23 articles' primary outcome measure was static posturography following training with the wearable postural stabilizer [39].

In general, a wide range of sensory biofeedback subtypes were observed. Specifically, 10/23 articles reviewed provided only haptic/vibrotactile feedback, 5/23 provided only visual feedback, and 4/23 provided only auditory feedback. In addition to the previous studies assessing unimodal biofeedback, some research studies implemented multimodal biofeedback (including >1 types of sensory biofeedback). Specifically, 2/23 utilized both auditory and visual feedback [5, 38], 1/23 utilized both vibrotactile and visual feedback [16], and 1/23 used all three types of feedback [15].

A majority (16/23) of the articles reported biofeedback to be administered in an instantaneous, concurrent "online" manner (e.g., exceeding a predefined absolute or relative threshold of a trigger variable). In addition to this, 3/23 articles reported providing continuous, concurrent "online" biofeedback (i.e., continuous feedback during a movement) which was always coupled with visual biofeedback [21, 42, 36]. Additionally, 2/23 articles reported administering biofeedback in two different ways, with visual always being continuous concurrent "online" and the other (haptic/vibrotactile and auditory) being provided instantaneously concurrent "online" [5, 15]. Of the articles included for review, 2/23 articles did not report the biofeedback triggers and timing [35, 39]. Further, no articles utilized a delayed, terminal "offline" type of sensory biofeedback.

Almost all (21/23) of the articles deemed that the implementation of their biofeedback intervention was effective at improving their respective outcomes, and there was no apparent bias towards any one population, healthy or clinical, in terms of effectiveness. One article by Ribeiro et al. [30] found that their intervention was not effective, and one article [39] noted that their intervention was effective in improving their secondary clinical outcomes (e.g., reduced falls risk, increased quality of life), however, it was not the superior intervention for their primary objective clinical outcomes (i.e., posturographic changes). The biofeedback types employed by the two studies who did not observe changes were not the same (auditory and vibratory, respectively), so there is no

Table 3 Quality assessments of included articles

Quality Index Item	Afzal et. al, 2015 [1]	Afzal et al., 2018 [2]	Bao et al., 2018 [3]	Breen, Nisar & ÓLaighin, 2009 [5]	Brodbeck et al., 2010 [6]	Cerqueira, Ferreira Da Silva & Santos, 2020 [7]	Chiari et al., 2005 [8]	Franco et. al, 2013 [11]
1	2	1	1.5	1	1.5	2	1	1
2	2	1.5	2	1	2	2	1	1
3	2	2	2	0.5	0.5	1	1	1.5
4	1.5	1	2	0	0	0	0	1
5	1.5	1	2	1	1.5	1.5	2	2
6	1.5	0.5	1.5	0	0	0	0	0
7	1.5	2	2	1.5	1	1.5	1.5	1
8	0.5	0	2	0	2	1.5	0	0.5
9	0.5	0.5	1	0.5	0	2	1	0.5
10	1.5	2	1	1	1.5	2	1	1
11	0.5	1.5	1	2	1	1.5	1.5	1.5
12	1.5	1.5	2	0	2	2	1	2
13	0.5	0	1.5	1.5	1	1	1	1.5
14	1.5	1	0.5	0.5	0.5	1	1.5	2
15	2	2	2	2	1	2	1.5	2
16	1.5	1.5	2	2	2	2	2	2
17	0.5	2	2	1	1.5	1	2	1.5
18	2	2	2	2	1.5	1.5	2	1.5
19	2	2	2	0	0.5	2	2	2
20	2	1	2	0.5	0	0	0.5	1
Total Score (/40)	28.5	26	34	18	21	27.5	23.5	26.5
Percentage	71.25	65	85	45	52.5	68.75	58.75	66.25
Quality Category	H	M	H	M	M	H	M	M
Quality Index Item	Gopalai et al., 2011 [12]	Kent, Laird & Haines, 2015 [15]	Kentala et al., 2003 [16]	Matheve et al., 2018 [21]	Nanhoe-Mahabier et al., 2012 [23]	O'Sullivan et. al, 2013 [26]	Ribeiro et al., 2020 [30]	Sienko et. al, 2010 [13]
1	0	2	2	2	1	1.5	2	0.5
2	1.5	2	2	2	2	2	2	2
3	1	2	2	2	2	2	2	1.5
4	1.5	2	2	2	1.5	2	2	1
5	2	1	1	0	0	1.5	0	2
6	0	2	0	2	0	0	2	1.5
7	2	2	1.5	2	2	2	1	2
8	0	2	0	0	0	0	1	0.5
9	1	2	2	2	1.5	2	0	2
10	1.5	2	1.5	2	0	2	0	2
11	0.5	1.5	1.5	2	1.5	2	0.5	2
12	1	2	1	0	1.5	0.5	1	1
13	0	2	0.5	2	0.5	1.5	0	1
14	2	1	1	0	0.5	0.5	0	1.5
15	2	2	2	1.5	2	2	1.5	2
16	2	1.5	2	2	2	2	1.5	2
17	2	2	1.5	2	2	1.5	1.5	1.5
18	1.5	2	2	2	2	2	1.5	2
19	2	2	2	2	2	2	2	2

Table 3 (continued)

20	0.5	2	0	2	1		2	1	0
Total Score (/40)	24	37	27.5	31.5	25		31	22.5	30
Percentage	60	92.5	68.75	78.75	62.5		77.5	56.25	75
Quality Category	M	H	H	H	M		H	M	H
Quality Index Item	Sienko et al., 2013 [32]	Stollenwerk et al., 2019 [35]	Stredova et al., 2017 [36]	Vignais et al., 2013 [38]		Volpe, Giantin, Fasano, 2014 [39]	Wong & Wong, 2008 [40]	Yoon et. al, 2015 [42]	
1	2	1	0.5	2		2	2	2	
2	1.5	0	0.5	2		2	0.5	2	
3	2	0	1.5	2		2	1.5	0	
4	0.5	0	1	0		2	0.5	2	
5	1	1.5	0	2		1.5	1.5	1	
6	0	0	0	0		0	0	2	
7	1.5	1	0.5	2		1.5	1	1.5	
8	2	1	0	0		0	0	0	
9	2	0.5	0	1.5		0	0	1.5	
10	1	1.5	1	2		0.5	2	2	
11	1	0	1.5	1.5		1.5	2	1.5	
12	0	2	0.5	1.5		0.5	1.5	0	
13	0.5	0	1.5	0.5		2	2	1.5	
14	2	2	0	0		0	2	1.5	
15	2	2	1	2		2	2	1.5	
16	2	0	0.5	2		0.5	1.5	2	
17	1.5	0	0	1.5		0	0.5	1.5	
18	1	1	1.5	2		2	1.5	2	
19	1	2	0	0.5		2	2	2	
20	1.5	1	0	1.5		2	0	1.5	
Total Score (/40)	26	16.5	11.5	26.5		24	24	29	
Percentage	65	41.25	28.75	66.25		60	60	72.5	
Quality Category	M	M	L	M		M	M	H	

discernible difference between effectiveness of biofeedback types.

Discussion

Wearable sensory biofeedback

The implementation of wearable sensor-mediated sensory biofeedback is becoming more broadly explored in the fields of clinical biomechanics and motor control as a means to assess spine posture and motor function. Given the recent uptake of wearable technologies, understanding the use of wearable sensor informed interventions to improve or alter clinically relevant motor outcomes is crucial. Given this, the aim of this study was to examine the types of wearable sensor-mediated biofeedback currently being employed to explore and optimize spine posture and motor function. It was expected that the types of biofeedback used throughout the literature would be varied. However, the findings of this scoping review aimed to synthesize data across multiple scientific domains that employ sensory biofeedback to identify potential gaps and areas for further study.

Quality of reviewed articles

In total, 23 studies were included for full-text review based on the inclusion criteria for this work. Following quality appraisal, some clear strengths of the reviewed literature emerged. First, the results of the quality appraisal suggest that many studies (20/23; 16/23) provided a proper description of biofeedback (i.e., type and implementation, respectively), as well as the objectives (14/23), findings of the research (21/23), and the full description

Table 4 Data extraction table

Reference	Aims	Sample	Sensor Type	Sensor Location	Task Description	Processed Sensor Outcome	Biofeedback Trigger	Biofeedback Type	Conclusions	Limitations
[1]	Investigate whether a haptic feedback system is effective in reducing postural sway in young healthy subjects and in improving mean velocity displacement and planar deviation in stroke patients	Young healthy and clinical (stroke patients); $n=16$ (8 healthy, 8 patients)	Smartphone with accelerometer and magnetometer)	1 sensor (attached to waist via leather belt)	Balance tasks after assumption of each of four distinct postures for 30 s (one foot on the ground; the Tandem Romberg stance; one foot on foam; and the Tandem Romberg stance on foam) with eyes closed. Patient eyes were not closed and assumption of the Romberg stance (only) was tested during a balance task 25 s in duration	Projection of trunk tilt; Mean Velocity Displacement; Planar Deviation; and the ML and AP Trajectories	When a subject exerted any force in the Yp axis of the haptic device	Haptic	Our kinesthetic haptic feedback system was effective to reduce postural sway in young healthy subjects regardless of posture and the condition of the substrate (the ground) and to improve MVD and PD in stroke patients who assumed the Romberg stance	Small sample size; relatively slow update rate; simplified estimation of trunk tilt projection in upright posture which cannot include the possible effects of motion at hip; lack of measurement of changes in dynamic balance; and no long-term follow-up
[2]	Assess the efficacy of using a wearable biofeedback device that generates light-touch biofeedback in aiding balance maintenance in stable and unstable conditions	Healthy young individuals; $n=7$	IMU (on-board inertial measurement unit)	1 sensor (4 RW's) worn on back (2 shoulder straps 1 waist strap)	Balance tasks under 12 trial combinations based on two conditions each of standing stance (tandem-Romberg, single leg), and surface types (foam, solid ground) and three of biofeedback device status (no device worn, device worn with no feedback, device worn with feedback)	Torso tilt angle in mediolateral plane	± 1° about the vertical	Haptic	Experimental trials supported the feasibility of the system as a balance training aid	Small sample size (7); heavy weight of sensor backpack can be uncomfortable for subjects; only provides balance cues in ML direction; study didn't identify balance recovery effects from added weight of sensor backpack

Table 4 (continued)

Reference	Aims	Sample	Sensor Type	Sensor Location	Task Description	Processed Sensor Outcome	Biofeedback Trigger	Biofeedback Type	Conclusions	Limitations
[3]	Assess the efficacy of long-term balance training with and without sensory augmentation among community-dwelling healthy older adults	Community dwelling older (65–85 y/o) adults; *n* = 12	IMU (iphone)	1 sensor (L4/L5 region) + 4 tactors (navel, lumbar spine, L/R sides of torso)	Performed six repetitions of six exercises selected from five categories (static standing, compliant surface standing, weight shifting, modified center of gravity, and gait)	Trunk acceleration/displacement	The tilt angle plus one half times the tilt angular rate for Categories 1, 2, 4 and 5, and as the tilt angle for Category 3 exercises	Vibrotactile	The findings of this study support the use of sensory augmentation devices by community-dwelling healthy older adults as balance rehabilitation tools, and indicate feasibility of telerehabilitation therapy with reduced input from clinicians	First, vibrotactile SA was only provided during a subset of exercises under the gait category; Second, correctness of exercise performance was not monitored during training; Third, small sample size; Finally, the information provided to the physical therapist by the smart phone balance trainer was limited to the number of step-outs in the six repetitions and the stability perception ratings from the participants
[5]	Comparing the efficacy of using a wearable sensor that detects bad cervical posture in healthy subjects for reducing percentage of time spent in bad cervical posture at computer with and without biofeedback	Regular computer users (no history of neck/back pain); *n* = 6	Accelerometer	1 sensor (C7)	Work at the computer system for two sessions of five hours each with and without the application of the biofeedback	Percentage of time spent outside cervical posture threshold with and without biofeedback	Visual feedback continuous; auditory outside range of -5° to 10°	Auditory and visual	The results from data collected during this study suggest that participants were able to maintain better cervical posture when working with the biofeedback system	Did not take lumbar or thoracic regions into account; cervical movement only monitored in sagittal plane

Table 4 (continued)

Reference	Aims	Sample	Sensor Type	Sensor Location	Task Description	Processed Sensor Outcome	Biofeedback Trigger	Biofeedback Type	Conclusions	Limitations
[6]	Address limitations of current conservative therapy, by automatically monitoring movement exercises in real time, generating a motivating, game-like visual feedback, and storing patients' performance data for later assessment	Clinical (chronic LBP or undergone back surgery); $n=26$	Inertial sensor modules	2 sensors (T12/L1 and L5/S1)	A combination of mobilizing exercises (ROM improving), stabilizing exercises (e.g., squats, lifting weight, sit-to-stand), and a game which works similar to a mobilizing exercise	Mobilization and stabilization exercises: the ratio of number of times that the range of motion limit was reached to the total number of attempts of a particular performance of the mobilizing exercise; Game exercises: The ratio of caught vs. missed balls is displayed as a score, and the final score is recorded as the success level of this exercise in the patients' therapy history.; Clinical evaluation: subjective satisfaction of system questionnaire	Ranges determined by therapists (adjustable range enabling therapist to set difficulty for an exercise unique to each patient)	Visual and ambient (lightbulb)	The abstract visual feedback that we designed was considered helpful. Ambient feedback in the form of the Lightbulb proved to be a very useful addition to the computer screen in a real-life therapy setting	N/A
[7]	Aims to empower operators with posture awareness and provide objective data to ergonomists	"Users"; $n=5$	IMU (3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer)	4 sensors (T4, each upper arm, back of head)	5 tasks: drive two screws into a robot end-effector at neck level (#1), chest level (#2), waist level (#3), and hip level (#4), and lifting a 1 kg box and place it at the top of a cabinet (#5)	Ergonomic risk level (each sample is converted from an analog angular value to a state)	When user exceeds recommended time outside threshold (individualized thresholds)	Haptic	The results showed that providing real-time biofeedback to the subject improves posture awareness, and has a significant impact on reducing the ergonomic risk, with reductions of up to 39.8% of the time spent in hazard postures	N/A
[8]	Describe the architecture and the functioning principle of this ABF system, and examine if that ABF benefits normal, healthy subjects most when sensory information is partly compromised	Normal, healthy individuals; $n=9$	Linear uniaxial accelerometer	1 sensor (L5 region)	Quiet standing (60 s) in three sensory conditions (eyes closed on flat ground; eyes open on foam; eyes closed on foam)	Trunk acceleration	Moving outside of the 'reference region' (defined as a function of an individuals height)	Auditory	This acoustic information helped subjects reduce postural sway, especially when visual and sensory information were compromised by eye closure and stance on foam	N/A

Table 4 (continued)

Reference	Aims	Sample	Sensor Type	Sensor Location	Task Description	Processed Sensor Outcome	Biofeedback Trigger	Biofeedback Type	Conclusions	Limitations
[11]	To assess the effectiveness of a system that monitors the trunk angular evolution during bipedal stance and helps the user to improve balance through a configurable and integrated auditory-biofeedback loop	Young healthy individuals; *n* = 20	IMU sensors on smartphone (accelerometer, gyroscope, magnetometer)	3 sensors on smartphone mounted on L5	Standing barefoot for 30 s with arms close to the trunk, and eyes closed in 2 stance conditions (feet 10 cm apart, tandem stance) and 2 experimental conditions (no feedback, with feedback)	(1) the root mean square trunk tilt in the ML and AP directions (RMS in dregree), (2) the energy of the angulation signal in the ML and AP directions (in deg), (3) the 95% spectral edge frequency of the trunk tilt in the ML and AP directions (SEF95 in Hz), and (4) the duration of instability expressed as the time elapsed outside the DZ (error time in s)	ML trunk sway moving outside the deadzone (set to 1°)	Auditory	Healthy individuals were able to efficiently use ABF on sagittal trunk tilt to improve their balance in the ML direction	N/A
[12]	Integrate an intelligent vibrotactile biofeedback system with wobble board training for ankle proprioception rehabilitation and conditioning	Healthy, young individuals; *n* = 12	IMU	1 sensor (trunk + wobble board)	Subjects were required to maintain balance on the wobble board in eyes-open and eyes-close conditions, both with and without feedback	Trunk angles	Minor or severe violation (A-P direction only)	Vibrotactile	The results observed an improvement in postural control with biofeedback intervention, demonstrating successfulness of the prototype	The current setup only allows for monitoring and feedback to be provided along a single plane
[15]	(i) test the hypothesis that modifying patterns of painful lumbo-pelvic movement using motion-sensor biofeedback in people with low back pain would lead to reduced pain and activity limitation compared with guidelines-based care, and (ii) facilitate sample size calculations for a fully powered trial	Clinical (sub-acute and chronic LBP); *n* = 112 (58 intervention, 54 control)	2 IMU's 2 EMG's	2 sensors (thoraco-lumbar junction and upper sacrum)	Various (clinician devised a patient-specific rehabilitation strategy designed to address any identified deficits in the patient's pattern of lumbo-pelvic movement and/or posture)	Self-reported pain intensity (Quadruple pain Visual Analogue Scale) and activity limitation (Roland Morris Disability Questionnaire and Patient Specific Functional Scale)	Exceeded a pre-determined angle for a sustained pre-determined period of time by the clinician	Visual and auditory/vibrotactile	Individualised movement retraining using motion-sensor biofeedback resulted in significant and sustained improvements in pain and activity limitation that persisted after treatment finished	Pilot trial involved co-funding and participation by the device manufacturer; Over the 12-month follow-up period the Guidelines based Care Group improved minimally; difference in the reference time period for QVAS at baseline compared with the reference period used at the follow-up time-points; the applicability of the results outside of the research context is constrained by the need for clinicians to be trained in the use of the ViMove system

Table 4 (continued)

Reference	Aims	Sample	Sensor Type	Sensor Location	Task Description	Processed Sensor Outcome	Biofeedback Trigger	Biofeedback Type	Conclusions	Limitations
[16]	Evaluate the impact of a vibrotactile balance prosthesis on the performance of balance-impaired subjects on a moving platform	Clinical (vestibular disorders); $n=6$	IMU (accelerometer and gyroscope)	1 sensor (L2-L3 region)	The training consisted of having the subject lean either backward or forward to move this icon to 6 designated targets: 3 in the front of center and 3 in the back of center; sensory organization tests 5 and 6	Body tilt angle	A tilt angle range is set individually for each subject, based on his or her maximum forward and backward tilt angles (on average, the maximum tilt angles were 10° forward and 8° backward)	Vibrotactile and visual (for some trials)	Able to reduce the AP body tilt in subjects with vestibular deficits using a simple precursor to a "balance prosthesis,"; vibrotactile feedback enabled our vestibulopathic subjects to remain standing instead of falling	The prosthesis precursor is too bulky to be of use in everyday life
[21]	(1) to assess whether sensor-based feedback is more effective to improve lumbopelvic movement control compared to feedback from a mirror or no feedback in patients with chronic low back pain and (2) to evaluate whether patients with CLBP are equally capable of improving lumbopelvic movement control compared to healthy persons	Healthy and clinical (chronic LBP); $n=108$ (54 healthy, 54 patients)	IMU (accelerometer, gyroscope, magnetometer)	3 sensors (L1, S1, 20 cm above lateral femoral condyle)	A waiter's bow, and a lifting task (start from a relaxed standing position and lift a 4 kg box with handles from a platform on the floor and to put it back down, while maintaining their lumbar curvature (i.e. not to flex or extend the lumbar spine))	Effectiveness of feedback between baseline and post-intervention kinematics (lumbar spine and hip angles) for patients; comparing kinematics between healthy participants and patients	Continuous	Visual	Sensor-based feedback is an effective means to improve lumbopelvic movement control in patients with CLBP	Motor learning was assessed only by transfer test, not retention; mobility of lower limb joints was not evaluated at baseline; only 3 sensors were used for measurement (only 2 for feedback)

Table 4 (continued)

Reference	Aims	Sample	Sensor Type	Sensor Location	Task Description	Processed Sensor Outcome	Biofeedback Trigger	Biofeedback Type	Conclusions	Limitations
[23]	To investigate the short-term carry-over effects of one training session involving real-time vibrotactile biofeedback, as compared to a similar session of non-biofeedback training in PD patients	Clinical (Parkinson's disease); *n* = 20	Angular velocity sensors	2 sensors (L1 and L3) + headband for biofeedback	Six gait tasks and six stance tasks that were presented in increasing order of difficulty. The gait tasks included: walking 9 m at preferred speed with eyes open and with eyes closed, 'get up and go' for 3 m (without turning), walking 9 m with a cognitive dual task (counting back in sevens), walking 9 m with a motor dual task (carrying a glass of water), and walking 15 tandem steps with eyes closed. The stance tasks included: standing with feet together with eyes open and with eyes closed, standing with feet together on foam with eyes open and with eyes closed, standing on one leg with eyes open, and tandem stance with eyes closed	AP and ML displacement of the trunk (angular velocity and sway angle)	40% of the 90% ranges of pitch and roll sway angular velocity derived during the second balance assessment of the first session	Vibrotactile	One session of balance training in PD using a biofeedback system showed beneficial effects on trunk stability	First, the present intervention was brief and not very intensive; examined a small number of PD patients with a mild disease severity and without cognitive decline; patients had a relatively good balance as indicated by the high Tinetti scores, limiting the generalizability of the findings

Table 4 (continued)

Reference	Aims	Sample	Sensor Type	Sensor Location	Task Description	Processed Sensor Outcome	Biofeedback Trigger	Biofeedback Type	Conclusions	Limitations
[26]	To investigate how sitting behaviour is related with seated LBD, and whether using postural biofeedback which is matched to the individual clinical presentation can reduce LBD among people with NSCLBP during a standardised seated task	Clinical (non-specific chronic LBP); $n = 24$	"Bodyguard" posture monitor with strain gauge	Spinal levels of L3 and S2	Sit as they normally would on a flat, leather stool without a backrest with their hips and knees flexed to 90° while watching a DVD for 2 h	Mean lumbopelvic posture and postural variation expressed as a percentage of total lumbopelvic ROM	Individualised threshold for each subjects biofeedback was established	Vibrotactile	This study demonstrated that using postural biofeedback to facilitate a more neutral and less variable sitting posture significantly reduced seated LBD in a single session among people with NSCLBP	Choosing a two-point increase for categorising participants as PDs was somewhat arbitrary; LBD and OBD still increased significantly over time on both days suggesting that intermittent periods of physical activity may be needed; as PDs reported significantly greater baseline disability than NPDs it suggests that greater central sensitisation among PDs contributed to the increased LBD reported during T1; No follow-up of the participants was included; participant blinding was almost impossible from nature of postural biofeedback so possibility of an enhanced placebo effect; Using a stool without a backrest does not reflect the type of seat most commonly used; Possible that discomfort may have been reduced simply due to task familiarity; Other potentially relevant parameters like muscle activation were not measured; assessor of seated discomfort was not blinded; Angular data are not provided with the posture monitor and increased forward lean can result in data exceeding the calibration value of 100% ROM

Table 4 (continued)

Reference	Aims	Sample	Sensor Type	Sensor Location	Task Description	Processed Sensor Outcome	Biofeedback Trigger	Biofeedback Type	Conclusions	Limitations
[30]	The aim was to assess the effectiveness of a lumbopelvic postural feedback device for changing postural behaviour in a group of healthcare workers	Adult healthcare workers; *n* = 130	Triaxial accelerometer	1 sensor (waistband)	Various activities of daily living & work-related activities	Total number of times the postural threshold was exceeded per hour in a working week	45° lumbar spine flexion (lasting 5 + sec OR less than 25 s following first sustained posture)	Auditory	Findings indicate that audio feedback provided by a postural monitor device did not reduce the number of times healthcare workers exceeded the postural threshold	Monitor was attached to waistband; monitor had to be replaced if monitor had significantly changed position
[31]	To investigate the effect of vibrotactile feedback during continuous multidirectional perturbations of a support platform using frequency-domain techniques and stabilogram diffusion analysis	Clinical (vestibular deficits); *n* = 8	2-axis IMU	1 sensor (lower back)	Subjects were instructed to stand with their eyes closed for all trials and move in such a manner so as to null any vibrations in response to 2-axis platform movements regardless of the display configuration	Power spectral density functions of body sway in the anterior–posterior (A/P) and medial–lateral (M/L) directions and transfer functions between platform motion and body sway	Tilt angle plus half the tilt rate exceeded a threshold of 1ο (1 subject used a 0.5οthreshold instead)	Vibrotactile	The reduction in gains of the frequency transfer functions computed for body sway responses in the A/P and the M/L directions suggests that the vibrotactile feedback improves the sensitivity of the human postural control system to external platform disturbances	N/A
[32]	To characterize the effects of two real-time feedback displays on locomotor performance during four gait-based tasks ranging in difficulty	Clinical (vestibular deficits); *n* = 7	IMU	1 sensor (lower back)	Slow and self-paced walking, walking along a narrow walkway, and walking on a foam surface	The root-mean-square (RMS) trunk tilt and percentage of time below the tilt thresholds	Subject-specific predefined tilt threshold; A tilt exceeding 1° (0.75° for one subject) activated the lowest tactor (low level); a tilt exceeding 50% of the subject's M/L limit of stability activated all three tactors (high level)	Vibrotactile	This preliminary study demonstrated that use of continuous vibrotactile feedback during challenging locomotor tasks allowed subjects with vestibular deficits to significantly decrease M/L RMS trunk tilt	Small sample size and a short training session

Table 4 (continued)

Reference	Aims	Sample	Sensor Type	Sensor Location	Task Description	Processed Sensor Outcome	Biofeedback Trigger	Biofeedback Type	Conclusions	Limitations
[35]	To systematically analyze geometric changes in posture as a result of postural training by a Gokhale Method teacher	"Users"; *n* = 425	Accelerometer	5 sensors (lumbar spine)	Sitting, standing, hip hinging	Compared snapshots of an unguided-guided posture pair based on features computed from the 2D spine curve geometry	N/a	Visual	For all three positions, sitting, standing, hip hinging, we found a significant change in posture between the sets of guided and unguided snapshot pairs	No information on participants gender, age, height or weight; number of clusters suggested by the geometry does not necessarily reflect the number of clusters found by the posture trainer; showed several samples per cluster to only one professional posture trainer for postural change evaluation
[36]	Elucidate if there is a significant difference between the ability to maintain balance with or without the biofeedback while standing and identify specific segments that takes place of motion solutions of postural problems	Healthy individuals; *n* = 10	Triaxial accelerometer	6 sensors (2 lower leg, 2 thigh, processus spinosus vertebrae L5 and C7)	3 postural tasks and 3 dynamic tasks. Postural: quiet standing with feet apart with eyes open, quiet standing with feet together with eye closed, quiet standing with feet apart with eyes open and with visual biofeedback. Dynamic: Shifting center of gravity while standing with feet apart with eyes open according to a biofeedback	Parameter SD VPG (sum of scatter of the acceleration in measured segments in 3D which shows changes in acceleration in every directions of Cartesian system) from the VBF tasks	Continuous	Visual	Tasks with VBF shows greater SD of VPG than without VBF which shows that the conscious correction of the COP interfere to cortical system of motoric control; in eyes closed are deviations of the posture are bigger compared to open eyes. The biggest accelerations were detected in C7 in eyes closed; detected that in open eyes majority of probands used ankle strategy for maintaining balance, eyes closed preferred knee and hip strategy	Can´t compare 2D and 3D data, which could cause disagreements with studies conducted in 2D

Table 4 (continued)

Reference	Aims	Sample	Sensor Type	Sensor Location	Task Description	Processed Sensor Outcome	Biofeedback Trigger	Biofeedback Type	Conclusions	Limitations
[38]	Introduce an innovative and practical system for ergonomic assessment of a worker's activity in realtime	Healthy males; *n* = 12	IMU	7 sensors (1 IMU for each upper arm, 1 IMU for each forearm, 1 IMU for the head, placed on the STHMD, 1 IMU for the trunk, located on the chest, and 1 IMU for the pelvis, placed on the sacrum)	The manual task was composed of four subtasks: (1) turning two hand levers by 90°, (2) removing four fuses at knee level, and putting them into a box, (3) taking a screwdriver, (4) unscrewing four screws of a transducer's covering and putting it down near the box, unscrewing four screws of an upper transducer's covering and putting it down near the box	Percentage of time spent in pre-defined RULA score ranges (global) and percentage of time spent at or above a predefined threshold per articulation or segment (local)	Visual (when local score was exceeded the following thresholds; shoulder and upper arm: 5, elbow and lower arm: 3, wrist and hand: 5, neck and head: 4, pelvis and trunk: 4) and auditory (when global score was 7 for a period of at least 0.5 s or when global score was between 5 and 6 for a period of at least 5 s)	Visual (local scores) and auditory (global score)	Real-time ergonomic feedback significantly decreased the outcome of both globally as well as locally hazardous RULA values that are associated with increased risk for musculoskeletal disorders	Epidemiological data supporting the suggested patterns is missing; RULA table lacks precision; RULA table uses basic calculations which can be considered as a weakness for some specific anatomical areas like the lumbar zone; this system is not able to individually evaluate a lift and it has not yet been tested in an industrial environment; not possible to know the influence of the cumulative time spent at each range on the risk of MSDs exposure; inertial sensors and magnetometers can suffer from drawbacks such as magnetic disturbances
[39]	To test the feasibility and effectiveness of a balance training program in association with a wearable proprioceptive stabilizer (Equistasi) that emits focal mechanical vibrations in patients with PD	Clinical (Parkinson's disease and history of at least one fall in the past); *n* = 40	"Equistasi" devices (wearable postural stabilizer)	3 sensors (over the 7th cervical vertebra and on each soleus muscle tendons)	Upright stance with the patient barefoot with the feet splayed out at 30 degrees, while keeping the arms alongside the body and staring at a fixed point marked on the wall at a distance of one meter at the height of the glabella of each individual for 51.2 s under each condition [with eyes open (EO) or closed (EC)]	Static posturography	N/a	Vibrotactile	A physiotherapy program for training balance in association with focal mechanical vibration exerted by a wearable proprioceptive stabilizer might be superior than rehabilitation alone in improving patients' balance	Cannot rule out the bias introduced by fluctuations in levodopa plasmatic concentration; sample size is small and results have to be replicated by larger trial; the execution of exercises were influenced by therapists expertise and patients' motivation; WPS were only tested on the neck and soleus muscles and not in other muscles involved in posture control

Table 4 (continued)

Reference	Aims	Sample	Sensor Type	Sensor Location	Task Description	Processed Sensor Outcome	Biofeedback Trigger	Biofeedback Type	Conclusions	Limitations
[40]	Introduce a method of using tri-axial accelerometers and gyroscopes to detect postural change in terms of curvature variation of the spine on the sagittal and coronal planes and demonstrate the performance of the posture monitoring system during daily activities	Healthy individuals; *n* = 9	Inertial (1 tri-axial accelerometer and 3 uni-axial gyroscopes per sensor)	3 sensors (upper trunk T1, mid-trunk T12 and pelvic level S1)	Left and right lateral bending, forward flexion (rounding of the lumbar spine to a "slouched" seated posture) from neutral sitting position (upright sitting), and stand-sit-stand	Tilting angles and trunk angles of the thoracic and lumbar regions, and angular velocity of trunk movements	Day 2 (sagittal plane: < 10°; coronal plane: ± 10°); day 3 (sagittal plane: < 5; coronal plane: ± 5°)	Auditory	Subjects could improve their posture when feedback signals were provided	N/A
[42]	To investigate the effects of visual feedback on internal oblique, external oblique, multifidus, and erector spinae and the kinematics of the trunk and pelvis between healthy and chronic low back pain	Healthy and clinical (chronic LBP); *n* = 20 (10 healthy, 10 patients)	Smart-phone (Clinometer software (Plaincode) and Mobizen software (Rsupport) were downloaded from the Google store and installed on the smart phone and computer)	1 sensor (T10-T12)	Raise right arm slowly and to straighten the right arm forward parallel to the floor without raising or dropping either shoulders. The subject was then instructed to extend the left hip backwards by raising and straightening the left knee parallel to the floor, with no rotation in the hip. During arm and leg lift in quadruped (ALLQ) position with VF condition, the subject was instructed to maintain the trunk angle in the computer monitor	Net angular displacement of the trunk (flexion/extension in sagittal plane, lateral bend in frontal plane, and axial rotation in transverse plane) and pelvis (anterior tilt/posterior tilt in sagittal plane, left pelvic drop/hike in frontal plane, and anterior/posterior axial rotation in transverse plane)	Continuous	Visual	VF applied through wireless smart-phone mirroring system has a selective positive effect on trunk muscles and pelvic movement and may be beneficial for CLBP patients	Only the static phases of trunk muscle stabilization exercises were investigated; compensatory movement or subtle differences in the degree of arm and hip lift were not fully controlled; a cross-sectional method with a relatively small sample size in young subjects was used; an order effect and 2 repetitions per condition (increasing variability and random error)

of any statistical analyses (18/23). In addition to these strengths, the quality appraisal also identified some systematic shortcomings across the surveyed literature. Specifically, most studies failed to adequately justify sample size (16/23), properly describe movement instructions (10/23), and provide adequate detail regarding raw signal handling and processing (14/23). Despite these limitations, these results may stem from the diverse nature of the research articles included in the current review. Specifically, many of the papers included were written as proof-of-concept studies with some using commercial equipment with closed-source algorithms limiting the description of any raw signal processing or handling information. Interestingly, given the novelty of wearable sensor-mediated biofeedback, approximately half of the studies included assessed the utility of these technologies on a clinical population which suggests a strong desire to use wearable sensor-mediated biofeedback as a clinical tool to (re)train spine movement, and to enhance motor function. These data further contextualize those reported in a recent systematic review evaluating the use of wearable technology to assess spine kinematics whereby almost all studies reported research conducted in a research laboratory [27]. Taken together the results of the current work and those presented previously (i.e., [27]) suggest the need for future work to continue working with specialized populations in real-world environments including the workplace and other settings which promote the completion of activities of daily living or therapeutic-style spine and trunk movements.

Descriptive aspects of reviewed articles

The data extraction procedure employed within this research uncovered several interesting trends throughout the sampled literature. First, the most common type of biofeedback employed across the studies assessed was haptic/tactile feedback (12/23). Although the motive for this apparent bias towards tactile biofeedback is unclear, many studies noted that haptic biofeedback tends to be easy to administer for the researcher, and easy to understand and respond to for the participants. Future work regarding user preferences across a range of sensory modalities would be warranted to further support any unimodal sensory feedback paradigm in specific clinical groups. Despite the absence of user preference data, many of the studies reviewed in the current work note a general improvement in spine-related motor outcomes in the studies evaluated that implemented haptic/tactile feedback. These outcome measures included lumbopelvic control (i.e., rhythm), time spent in harmful positions, posture and balance awareness, and trunk stability. Despite this prevailing bias towards haptic feedback, there remains a lack of consensus about the most appropriate means of administering this type of biofeedback. For example, only about half of the research studies (7/12) administer haptic feedback to the lumbar region (i.e., skin of the trunk dorsum), with other studies administering the feedback at a secondary location (i.e., headband) despite the IMUs being fixed to the low back (e.g., [23]). There was also a wide variation in the timing and structure of any sensory feedback in addition to variation in the anatomical location of the sensory feedback. Some studies administered graded continuous vibrotactile feedback depending on various pre-determined absolute or relative threshold values (e.g., [13, 32]), and some adopted a simple instantaneous "on" or "off" approach (e.g., [2, 16, 26]).

The timing of the delivery of the feedback varied, with a mix of instantaneous "on" or "off" approaches and continuous delivery, with some studies implementing both approaches across one single or multiple sensory modalities. In general, the differences in timing of delivery are dependent on the sensory modality being targeted, but remained relatively consistent within types of biofeedback. For example, every instance of visual biofeedback reviewed in the present paper involved the continuous delivery of a target variable, and a majority (11/12) of vibrotactile feedback was instantaneous, informed based on pre-defined thresholds. However, auditory feedback was administered using both methods (including on/off stimuli, and those implemented in a continuous fashion with varying tones/pitches). Given the range of different modalities evaluated, the lack of consensus regarding the timing of delivery still presents a challenge as different modalities may be leveraged in contrasting ways to optimize varying clinical outcomes. Further work is required to optimize the anatomical location, trigger/threshold, and the waveform characteristics of any supplementary vibrotactile feedback, including a justification of these parameters to elicit an optimal motor response outcome.

There were approximately equal number of studies investigating healthy participants (10/23) and clinical populations (9/23); however, only two studies [1, 42] compared clinical and healthy participants. This divide in the research may be due to the high number of validation-type studies included within this scoping review, given the novelty and growing interest regarding wearable sensor-mediated biofeedback. Future work is needed to optimize the implementation of sensory feedback for those with and without motor impairments related to the spine, especially if any motor impairments are accompanied by apparent sensory deficits. There is agreement in the literature regarding inertial sensors as the most common sensor type used in this area of research (21/23). Furthermore, the results of the current work are in agreement with recent systematic reviews investigating wearable sensors in spine posture analysis [27, 34]. Specifically, IMU's can be cost-effective to acquire and maintain, are user-friendly, and able to produce easily interpretable results for clinicians and researchers alike. Additionally, they have been found to be reliable at measuring spine posture and movements, and can be a valuable tool to provide real-time biofeedback [34].

Clinical applicability

As noted, clinical presentations of low back disorders can be complex, and often non-specific. This apparent heterogeneity of individual responses to LBP suggests that the implementation of wearable sensor-mediated biofeedback into clinical settings also needs to be optimized for varying use cases. At present there is a lack of evidence for specific motor impairments associated with the development and chronicity of LBP; however, it is possible that through guided interventions using sensory feedback motor impairments may be reduced. The current scoping review presents a clear consensus towards implementing IMU hardware to extract biomechanically relevant spine and trunk kinematics. Further, a large majority of studies included in this review leverage haptic/vibrotactile feedback from IMU hardware. The lack of consensus is apparent in the timing and design of any IMU-derived vibrotactile feedback. Given this, it is likely that any sensory feedback parameters need to be optimized for individual clinical use cases. For example, future research could aim to investigate the most appropriate feedback administration (i.e., continuous or instantaneous) in individuals presenting with LBP and apparent sensory deficits. Further, it could be of interest to assess the use of tonal stimuli (i.e., varying in amplitude/frequency) with this population, and how it may be best applied to these users in an acute training framework to enhance the individual detection of specific spine/trunk postures given their sensory deficits. Such sensory feedback could be systematically reduced over time to encourage the dependence on natural stimuli to cue body postures and movements, and to improve the control of spine and trunk movement. Additionally, triggers could be re-evaluated over time to enhance individual lumbar range of motion (ROM) while concurrently limiting pain avoidance behaviours. In line with this, it should be noted that special consideration should be taken when deciding what type of biofeedback to utilize specific to various clinical populations and their deficits (e.g., sensory processing deficits).

Practicality & future directions

Although the study of wearable sensor-derived biofeedback is growing throughout the scientific literature, the practicality and scalability of such sensory feedback in a therapeutic context remain unknown. There is a strong theoretical basis for the use of sensory cues to evoke motor changes of the spine and trunk [4, 28], however, it is clear that future work is required to both (1) optimize the structure of any sensory feedback to individual use cases and (2) understand individual preferences and compliance to any sensorimotor training paradigm leveraging wearable technology. Given this, future work should aim to address the relative strengths of varying sensory feedback types, timing, triggers, locations, and magnitudes across a wide range of use cases, while also considering individual preferences to such feedback in day-to-day and clinical environments. This scoping review is limited as it is only up to date as of September 2020, so further up-to-date evidence in these areas would be beneficial as the field is rapidly growing.

Conclusions

The results presented here synthesize the literature aiming to provide wearable sensor-mediated sensory feedback to facilitate motor adaptations relating to movement of the spine. The general findings of this scoping review found overall positive effects of wearable sensor-mediated biofeedback training on clinically relevant outcomes (i.e., spine posture, ROM and/or balance). This evidence suggests that this technology can be used as a clinical modality to improve spine motor function and posture. Care needs to be taken to properly report any motor task, and raw signal processing. Further, future work is necessary to further optimize the use of vibrotactile feedback as a biofeedback modality to elicit motor learning. Specifically, future work is needed to optimize the anatomical location, trigger/threshold, and waveform characteristics of any supplementary vibrotactile feedback. Collectively the research papers evaluated suggest strong promise in the use of biofeedback to complement the current uptake of wearable sensors in spine posture and movement retraining.

Supplementary Information

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Supplementary Material 1.

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Authors' contributions

AB and SMB were responsible for the conceptualization and development of the study and design and were major contributors in writing the manuscript. JN and AB performed all record identification (i.e., acquisition), assessment of texts for eligibility and quality assessment of articles. HM and AB were responsible for the data extraction (i.e., synthesis) from eligible articles. All authors read and approved the final manuscript.

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Availability of data and materials
All processed data generated or analysed during this study are included in this published article. Raw data can be provided upon reasonable request to the corresponding author (SMB).

Declarations

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Not applicable.

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The authors declare no competing interests.

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