Scandinavian Journal of Child and Adolescent Psychiatry and Psychology
Vol. 8:48-69 (2020) DOI 10.21307/sjcapp-2020-006

Review **Open Access**

The use of wearable technology to measure and support abilities, disabilities and functional skills in autistic youth: a scoping review

Melissa H. Black[1,2], Benjamin Milbourn[1,2], Nigel T. M. Chen[1,2], Sarah McGarry[1], Fatema Wali[1], Armilda S. V. Ho[1], Mika Lee[1], Sven Bölte[1,2,3,4], Torbjorn Falkmer[1,2,5], Sonya Girdler[1,2]

[1]School of Occupational Therapy, Social Work and Speech Pathology, Curtin University, Perth, Western Australia; [2]Curtin Autism Research Group, Curtin University, Perth, Western Australia; [3]Center of Neurodevelopmental Disorders (KIND), Centre for Psychiatry Research; Dep. of Women's and Children's Health, Karolinska Institutet & Stockholm Health Care Services, Region Stockholm, Stockholm, Sweden; [4]Child and Adolescent Psychiatry, Stockholm Health Care Services, Region Stockholm, Stockholm, Sweden; [5]Pain and Rehabilitation Centre, Dep. of Medical and Health Sciences, Linkoping University, Linkoping, Sweden

***Corresponding author:** melissa.black@curtin.edu.au

Abstract

Background: Wearable technology (WT) to measure and support social and non-social functioning in Autism Spectrum Disorder (ASD) has been a growing interest of researchers over the past decade. There is however limited understanding of the WTs currently available for autistic individuals, and how they measure functioning in this population.
Objective: This scoping review explored the use of WTs for measuring and supporting abilities, disabilities and functional skills in autistic youth.
Method: Four electronic databases were searched to identify literature investigating the use of WT in autistic youth, resulting in a total of 33 studies being reviewed. Descriptive and content analysis was conducted, with studies subsequently mapped to the ASD International Classification of Functioning, Disability and Health Core-sets and the ICF Child and Youth Version (ICF-CY).
Results: Studies were predominately pilot studies for novel devices. WTs measured a range of physiological and behavioural functions to objectively measure stereotypical motor movements, social function, communication, and emotion regulation in autistic youth in the context of a range of environments and activities.
Conclusions: While this review raises promising prospects for the use of WTs for autistic youth, the current evidence is limited and requires further investigation.

Keywords: Autism Spectrum Disorder; physiology; sensors; wearable devices; ICF

Introduction

Advancements in health monitoring have allowed for the development of external wearable systems, capable of unobtrusively capturing behavioral and physiological data in real-time. These systems, referred to as 'wearable technology' (WT) are devices worn externally, with built-in electronic functions utilized during the course of activity. Common WTs include fitness and activity trackers, smartwatches, and smart glasses, which measure a range of physiological and behavioral functions including heart rate, skin conductance, and eye gaze, among others (1). WTs are capable of providing assistance in completing cognitive and emotional tasks that demand limited intellectual, mnestic, affective and communicative resources, and record accompanying objective physiological and motor parameters, supporting participation in everyday activities and the documentation of physical correlates (1).

WTs present intriguing avenues for monitoring health (2) and functioning in clinical conditions (3). Unlike traditional methods of monitoring physiological activity and behavior, WTs have the potential to provide real-time and objective measures of activity during day to day life (3, 4). These technologies may show promise in expanding opportunities to improve understanding of clinical conditions and through providing a means to continuously measure and monitor daily life functioning, may contribute novel individualized intervention and treatment (4, 5).

Autism Spectrum Disorder (ASD) is a condition where WTs are of increasing interest (6). Autistic individuals experience impairing difficulties in social interaction and communication, and atypical restrictive or repetitive behaviors and interests and altered sensory processing, hampering adaptive functioning (7). While ASD is a heterogeneous condition, with variable impacts on functioning (8), these core characteristics pose significant barriers to participation and engagement.

WTs may provide a multitude of options to measure the physiological and behavioral functioning of autistic youth, as well as providing opportunities to support participation and engagement in various life domains. In particular, the autonomic nervous system (ANS), which provides an index of one's emotions and arousal levels, and influencing behaviour is commonly atypical in autistic individuals (9-12). Physiological markers indicative of ANS activity and measurable using WTs include heart rate, electrodermal activity, and body temperature, allowing insights into physiological responses not ordinarily objectively observable. Feedback on ANS changes has been proposed to have the potential to support the functioning of autistic individuals through enabling monitoring of activity and provision of feedback, and facilitating effective functioning in everyday (i.e. social) situations (13, 14).

A recent systematic review explored the use of WTs and mobile technologies for autistic individuals, finding that while promising, these technologies require additional investigation (15). It may be argued that there remains limited evidence and comprehensive understanding of the use of WTs for autistic individuals, and the functions that they measure and the contexts in which they are used. The International Classification for Functioning, Disability and Health Child and Youth Version (ICF-CY) provides a standardized framework to explore the factors influencing functioning, inclusive of body functions and structures, activities and participation and environmental factors (16). Recently the ASD ICF Core-sets, consisting of codes most relevant to ASD were developed (8), emphasising the role of specific contextual factors in understanding functioning in the autistic population (17). Providing a bio-psycho-social framework and a standardized means of examining functioning in ASD, the ASD ICF Core-sets provides a valuable tool in exploring factors relating to functioning in autistic populations, and has been used in previous reviews exploring the functioning of autistic individuals (18). The ASD ICF Core-sets may be particularly useful when examining the use of WTs, enabling a comprehensive exploration of how physiological and other functions (body functions) measured by WTs can provide insight into the abilities, disabilities and functional skills (activity and participation) of autistic youth within various contexts (environment). While the review by Koumpouros and Kafazis (15) explored both WT and mobile technology more generally, this review focuses specifically on WTs that are available to measure and support functioning in autistic youth, mapping the functions they measure according to the ICF Core Sets for ASD and the ICF-CY, enabling a comprehensive understanding of the use of WTs to assess abilities, disabilities, and functional skills.

Methods

Design

A scoping review exploring and synthesizing literature examining WTs assessing function in autistic youth was undertaken. To facilitate an extensive, comprehensive and rigorous search of the literature, Arksey and O'Malley's (19) methodological framework for scoping reviews and recommended methodologies by Daudt et al., (20) and Levac et al., (21) were utilized. Results were subsequently linked to the ASD ICF core-sets.

Search strategy

Four online databases including Medline, Scopus, Web of Science, and ScienceDirect were searched for literature examining WTs for autistic youth between 2008 and October 2018. A combination of key term and Boolean searches were conducted, with searches tailored to each database. Key terms were truncated (indicated by "*") and included *autis**, *ASD*, *Asperger**, *child developmental disorder**, *pervasive development* disorder**, *PDD-NOS*, *wearable*, technolog**, *smart**, *device**, *robot**, and *sensor** The literature search strategy was executed in consultation with an expert ASD research review group including researchers and clinicians experienced in conducting ASD research, and guided by a librarian with research expertise in health and rehabilitation sciences.

Study selection

Studies were included if they (a) examined the use of WTs, (b) included a subgroup of autistic participants according to the *International Statistical Classification of Diseases and Related Health Problems, 10th Revision, Fifth Edition (ICD-10)* (22) or the *Diagnostic and Statistical Manual of Mental Disorders-Fourth Edition, Text Revision (DSM-IV-TR)* (23) or *Fifth Edition* (7), (c) were peer-reviewed articles that are of full-text or detailed abstracts published within the last 10 years, and, (d) were available in English. Finally, as this review sought to examine the use of WTs in youth, studies with participants aged 20 years or younger (mean years) were included. Articles were excluded if they (a) primarily examined participant groups with a diagnosis of with Rett Disorder/Syndrome due to specific genetic grounds (24), or (b) were a book or book chapter, a review paper or grey literature (with the exception of conference proceedings). No limits were placed on the purpose of the WTs. Four authors reviewed the articles independently for inclusion. Uncertainty relating to the relevance of studies was discussed with the expert ASD research review group and the authorship team, which met regularly (once monthly). Subsequently, a concordant list of studies meeting inclusion criteria was developed.

Charting the data

A standardized data charting table, guided by Arksey and O'Malley (19) framework was utilized to extract relevant data from the selected articles. Descriptive study characteristics were charted including; first author, year of publication, study design, participants, nature/type of WT, function assessed/measured by the WT, data location and study setting, outcome measure/data collection method, key findings and quality of evidence. Data charting was undertaken by four authors who independently extracted data to ensure inter-author reliability. Extracted data were reviewed by a fifth author to ensure accuracy.

Assessment of methodological quality

The Qualsyst (25) was used to critically appraise and determine the methodological quality of the included studies. The tool consists of a checklist of 14 items for quantitative studies and 10 items for qualitative studies (25). Scoring criteria included evaluation of the objectives, study design and methods, analysis, and reporting of results and conclusions. For each item, criteria are allocated a score of '2' (yes), '1' (partial) and '0' (no). At least two reviewers independently assessed each study with the aid of the relevant tool. Using the scoring system provided by the checklist, articles were assigned a score corresponding to their quality (25). The strength of the evidence was represented with percentage scores in categories of 'Strong' (score of > 80 %), 'Good' (70-80 %), 'Adequate' (50-70 %) or 'Limited' (< 50 %) (26). Discrepancies between reviewers were resolved by discussion until consensus was reached.

Collating, summarizing and reporting the results

Extracted evidence was analyzed in two stages. The first stage involved descriptive and content analysis, while the second stage involved linking data to the ICF Core sets for ASD and the ICF-CY. Descriptive and content analysis undertaken in stage one included exploration of the study design, methodological quality as evaluated using the Qualsyst (25), data location, study setting and the WT discussed. Due to the heterogeneous and varied ways in which WTs have been used for autistic youth, and in taking the perspectives of families of autistic youth, WTs were further synthesized in regard to 1) the purpose of the WT and 2) the types of WTs available.

Following descriptive and content analysis, studies were linked to the ASD ICF Core-sets (8) and the ICF-CY (16) to examine the specific functions measured and targeted by the WTs. The ICF Core Sets for ASD were selected as they provide the ICF codes most relevant to autistic individuals, consisting of 111 second-level categories derived from the ICF (8). These ASD Core-sets have similarly been used in a previous scoping review (18). Prior to the linking of the data, meaningful concepts were first extracted in relation to three groups: 1) the functions measured by the WT (e.g., heart rate) 2) the functions targeted by the WT (the purpose of the WT, for example stress management), and 3) the context in which they were implemented (e.g., in the classroom). These concepts were extracted in accordance with guidelines for ICF linking (27, 28) whereby each meaningful concept referred to the intended meaning of units of text extracted from the articles. Meaningful concepts were subsequently linked to the first and second levels of the ASD ICF Core-sets under the domains of body functions, body structures, activity and participation and environment. The ICF-CY supplemented the ASD ICF Core-sets and enabled linking to the third and fourth levels of the ICF. Linking was conducted in accordance with guidelines outlined by Cieza et al. (27, 28). Concepts which were related to health conditions were coded as 'hc', concepts relating to personal factors were coded 'pf', concepts considered too broad to be defined were coded as not definable 'nd' and concepts not covered in the ICF were coded as not covered 'nc'. The linking results are presented using absolute and relative frequencies. The calculation of these frequencies was conducted using rules provided by Selb et al. (29), whereby codes occurring twice in a category were counted only once for the purposes of analysis. Linking of each meaningful concept was undertaken by two authors experienced in ICF linking with consensus reached through discussion.

Results

A total of 319 articles were identified from electronic searches of Medline (k = 42), Scopus (k = 144), ScienceDirect (k = 46) and Web of Science (k = 87). Of these articles, 117 were excluded due to being duplicated, resulting in 202 studies being screened at the title and abstract level. Following screening, 128 articles did not meet inclusion criteria and were subsequently excluded. The full-texts of the remaining articles (k = 74) were retrieved and assessed for eligibility criteria. A further 41 studies were excluded following full-text review due to the following reasons (i) inappropriate participant sample, (ii) not WT, (iii) inappropriate study type, (iv) published prior to 2008. A total of 33 studies remained and were included in the scoping review (Figure 1).

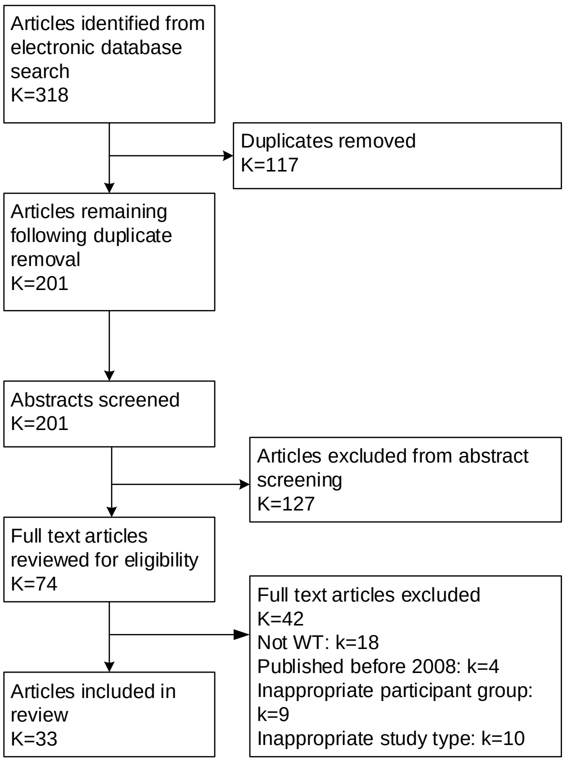

FIGURE 1. Study selection process

Study design

The 33 studies included consisted of a range of study designs. The majority of articles were considered quantitative in nature (k = 15), six were qualitative and 12 were considered mixed methodology. Articles were classified as mixed methodology if they included both quantitative analysis as well as elements of qualitative methodologies including subjective participant observation or feedback. Table 1 presents the extracted data for the included studies.

Methodological quality

The methodological quality of the articles ranged from limited to strong (Table 1). Eighteen studies were research articles with the remainder (k=15) being conference papers. Articles were primarily of adequate methodological quality (k=22). As many of the articles were conference papers and pilot studies, common limitations included small sample sizes and inadequate reporting of experimental conditions and lack of rigor in qualitative analysis.

Data location and processing

As shown in Table 1, physiological and behavioral data obtained from the WTs were primarily processed and/or stored on a personal computer, control unit, or database (k = 20). A number of devices also had processing capabilities embedded within the devices, with some enabling real-time feedback to be provided to youth, such as smart glasses to support social functioning (k = 10), or smartwatches to provide self-regulatory strategies (k = 1). Several devices also interfaced with tablets or smartphones, enabling individuals to monitor physiological activity or customize feedback (k = 9). While not linked to the processing of the WT data, one study used a mobile application allowing caregivers and clinicians to record symptoms, interventions, and progress. Through linking this data in the database, opportunities were provided to correlate caregiver reported events with data collected through the WT (30).

Study location

WTs were studied in a range of environments (Table 1) including laboratory or clinical settings (k = 18), semi-naturalistic settings, such as within the context of therapy (k = 8), and naturalistic settings (k = 14), including the home (k = 6), classroom (k = 5), clubs (k = 1) and other (k = 2).

Purpose of wearable technologies

WTs were used for a number of purposes. The most common purpose of the WTs was for intervention (k = 20). WTs were used as the interventions themselves (k = 15), for example, providing self-regulation strategies, or training, while other WTs (k = 5) were used to monitor participant behavior and outcomes during intervention sessions. Thirteen WTs were used within basic research settings, with the aim of obtaining objective data within a specific experimental or environmental set-up. A number of WTs (k = 7) which were evaluated in basic research settings, were, however, also reported to be developed with the aim of being applied for intervention purposes.

TABLE 1. Summary of purpose of WT and ICF codes

Author (year)	Design	Participants	Wearable technology	Function assessed	Data processing/ location, study setting	Measures of WT	Key findings	Quality
Quantitative								
Albinali et al., (2012)	Case series Case study	Study 1: Children and young adults with ASD; n=6 (12-20 years) Study 2: n=1 (participant of Study 1)	Three wireless accelerometers worn on wrists and torso	SMM	PC, naturalistic (classroom) and clinical settings	SMM classification Inter-rater agreement between real-time and offline annotators (Study 1); and expert and non-expert annotators (Study 2)	Accelerators had good recognition accuracy of SMM in classroom. Fair agreement between expert and non-expert annotators of SMM.	Strong (86%)
Billeci et al., (2016)	Case series	Male children with ASD, n=5, 6-8 years, mean age: 7.2 (SD: 0.83)	Enobio headset (EEG) ECG chest belt	Social function, imitation	CU, semi-naturalistic setting (therapy)	Observation EEG: Frequency power and coherence ECG – HR, HRV, RSA, root mean square of – successive- differences	WTs able to detect level of engagement during play therapy sessions.	Adequate (68%)
Di Palma et al., (2017)	Case series	Male children with ASD, n=5, 6-8 years, mean age: 7.2 years, (SD: 0.83)	ECG chest belt	Social function	CU, semi-naturalistic settings (therapy)	HR (bpm) HRV (Root mean square of the successive differences, RSA	WT feasible method for quantifying longitudinal variations in autonomic nervous system activity during therapy.	Adequate (63%)
Funahashi et al., (2014)	Case-control	Male child with ASD and TD male, 10 years of age	EMG worn on sides of the face, secured by a plastic structure	Social function, emotional regulation, verbal communication	PC, semi-naturalistic setting (therapy)	Time spent smiling (secs per session) Observation of positive and negate social behavior (coded)	WT reliably quantify smiles during animal-assisted therapy.	Adequate (59%)
Goodwin et al., (2014)	Follow-up case series	Children and young adults with ASD, n=6 (same participants from Albinali et al., 2012 study, 3 years later), 12-20 years	Three wireless accelerometers worn on the left and right wrists and torso	SMM	PC, naturalistic setting (classroom)	SMM classification	Classification of SMM in simple experiments was good but more variable in challenging experiments.	Strong (81%)
Hirokawa et al., (2016)	Case series	Individuals with ASD, n=10 (7 males, 3 females), mean age: 11.4 years	EMG worn on sides of the face, secured by a plastic structure	Social function, emotional regulation	PC, clinical setting	Accuracy of smile detection	WT could detect smile with high reliability for majority of participants. Measuring synchronization between smile and facing behavior showed typical pattern of expected results (less coordination) but	Adequate (59%)

							some participants showed different synchronization patterns.	
Magrelli et al., (2013)	Case-control	Children with ASD, n=14 (9 male, 5 female), 2-11 years, mean age: 6.08 year (SD: 2.03). TD children, n=17 (9 male, 8 female), 3-6 years, mean age: 3.99 years (SD: 1.27)	WearCam (cameras and mirror mounted on headband)	Social function, social orientating	PC, clinical setting	Distance between gaze of children's and adult's face Durations of the first fixations to facial expression Reaction times (seconds)	WT able to quantify gaze differences and overt shifts in attention between ASD and TD children	Strong (95%)
Magrelli et al., (2014)	Case-control	Children with PDD, n=13 (5 females, 8 males), 3-10 years, mean age:6.17 years (SD: 2.40) Control: TD children, n=13 (5 females, 8 males), 2-6 years, mean age: 3.68 years (SD: 1.29)	WearCam (cameras and mirror mounted on headband)	Social function, social orientating	PC, clinical setting	Proportion of time spent looking at area of interest (seconds) Frequency (Hz) and duration (seconds) of gaze episodes Proportion of time a face appeared in their field of view (broad and middle)	WT able to quantify gaze behavior in ASD and TD groups.	Strong (95%)
Mazzei et al., (2010)	Case-control	Phase 1: Child with ASD: n=1, 7 years. TD child: n=1, 8 years Phase 2: Individuals with ASD, n=4 (3 male, 1 female), 7-20 years old.	HATCAM mounted on head Sensorised shirt	Social function, emotion recognition	CU, semi-naturalistic setting (therapy)	Eye gaze direction and head orientation (attention to face) HR, HRV, respiratory rate, skin temperature, skin conductance	WTs capable of monitoring attention to face and physiological arousal during FACE intervention and enabled robot control system (robotic face) to adapt to participants perceived emotion.	Limited (36%)
Min et al., (2009)	Case series	Children with ASD, n=2	Wireless accelerometer worn on the wrist and back	SMM and self-injurious behavior	PC, semi-naturalistic (therapy) and naturalistic settings (home)	SMM Classification	Single sensor worn on the back could accurately detect body rocking and hand flapping. Flapping events more accurately detected by wrist sensors.	Adequate (54%)
Min et al., (2010)	Case series	Children with ASD, n=4	Wireless accelerometer worn on wrist and back	SMM and self-injurious behavior	PC, semi-naturalistic (therapy) and naturalistic settings (home)	SMM classification	Classification of behaviors using accelerometer was improved through new methods.	Limited (45%)
Min et al., (2011)	Case series	Children with ASD, n=4	Wireless accelerometer worn on wrist, ankle and upper body	SMM and Self injurious behavior	PC, semi-naturalistic (therapy) and naturalistic settings (home)	SMM Classification	Detection of behaviour based on accelerometer can better account for variability between individuals and individual behaviour changes over time, through an alternate method of classification training.	Limited (45%)

							This updated method had comparable accuracy to previous methods that did not accommodate as much variability.	
Rad et al., (2017)	Case series	Simulated data: TD individuals n=5 (2 male, 3 female) Real data: Data from participants in previous study (Goodwin et al., 2014), children with ASD, n=6, 12-20 years	Simulated: EXLs3 sensor worn on wrist Real: Three wireless accelerometers worn on both wrists and torso	SMM	PC, clinical and naturalistic setting (classroom)	SMM classification	Updated software architecture was able to more accurately detect stereotypical motor movements through better accommodating for inter-subject variability	Adequate (68%)
Takahashi et al., (2016)	Case series	Male children with ASD, n=4, 3.8 – 5.5 years	Smart Clothe ECG sensor embedded in sleeve cuff	Emotion regulation	Tablet, Semi-naturalistic setting (therapy)	HR, HRV (R-R intervals on ECG waves)	Three out of four children tolerated WT. High reliability in measuring indicators of mental stress when performing tasks that require minimal movement.	Adequate (63%)
Vahabzadeh et al., (2017)	Case series	Children, Adolescents and young adults with ASD, n=8 (7 male, 1 female)	Empowered Brain System (smart glasses)	Social function, emotion recognition	WT, clinical setting	Attention deficit hyperactivity disorder (ADHD) symptoms (measured by Aberrant Behavioral Checklist)	All participants completed intervention without negative effects. The majority of participants showed reduction in ADHD-related symptoms 24 hours and 48 hours after intervention.	Adequate (68%)
Mixed methodology								
Billeci et al., (2018)	Case-control	Toddlers with and without ASD. ASD: n=20 (14 male, 6 female), Mean age: 2.18 (SD: 0.3) TD: n=20 (15 male, 5 female), mean age = 2.18 (SD: 0.31)	ECG Chest strap	Social function (joint attention)	PC, Clinical setting	HR (time domain: bpm, Standard deviation of NN intervals, coefficient variation, pNN10, frequency domain: Low frequency, high frequency, normalized low frequency, normalized high frequency), ADOS-G, Child behavior Checklist, Griffiths Mental Development Scales, Video observation	WT was capable of capturing ANS response during task. Results indicate that toddlers with ASD may have autonomic dysregulation, and possibly, reduced mental engagement during joint attention. WT did not cause observable annoyance to participants. All participants successfully completed task without sensory-motor and/or behavioral issues in wearing WT.	Quantitative Good (71%) Qualitative Strong (75%)
Daniels, Schwartz et al., (2018)	Case series	Children with ASD, n=14 (11 male, 3 female), Mean age: 9.57 (SD: 3.37)	SuperPower Glass system (smart glasses)	Emotion recognition	WT, Smartphone and database, naturalistic setting (home)	Autistic-like traits- Social Responsiveness Questionnaire (SRS-2) Labelling of emotions	WT resulted in reduced autistic-like traits, improved emotion recognition skills. Parents report system is engaging and useful.	Quantitative Strong (86%) Qualitative Limited

						Semi-structured interview		(45%).
Daniels, Haber et al., (2018)	Case-control	Children with and without ASD Hypothesis 1: n=43, ASD: n=23 (19 male, 4 female), 6-17 years, mean age: 11.65 (SD: 3.20). TD: n=20 (14 male, 6 female), 7-17 years, mean age: 11.55 (SD: 3.09). Hypothesis 2 and 3: n=33, ASD: n=16 (13 male, 3 female), 16 -17 years, mean age: 12.13 (3.31). TD: n=17 (9 male, 8 female), 8 – 17 years, mean age: 11.53 (SD: 2.48)	SuperPower Glass system (smart glasses)	Emotion recognition	WT, Smartphone and database, clinical setting	Interview Emotion recognition accuracy Classification of ASD and TD.	System fitted well and was not over stimulating for children. Children had difficulty reading visual cues from heads up display. Emotion information provided by WT associated with an increase in emotion labeling accuracy. Algorithms trained to classify ASD and TD performed no better than chance using the same nested cross-validation scheme. Differences between and TD depend on which expressions were confused.	Quantitative Strong (86%) Qualitative Limited (45%)
Hachisu et al., (2018)	Case series	Study 1: Children with ASD, n=6 (3 male, 3 female), 13 - 14 years Teachers, n=4 (2 male, 2 female) Study 2: Children with ASD, n=4 (2 male, 2 female), 15-17 years	FaceLooks Smart headband	Social function	Tablet/smart-phone, naturalistic setting (classroom)	Observation Face to face duration	No child removed WT. Some participants reported WT was too small to wear for long periods. Total duration of face-to-face durations increased with WT feedback, but some participants were not aware of the feedback rule.	Quantitative Strong (81%) Qualitative Adequate (65%)
Jiang et al., (2016)	RCT	Children with ASD, n=10 (7 male, 3 female), 7-14 years	ProCom (chest worn proximity sensor)	Social function, interpersonal space	Smartphone, clinical setting	Proximity (distance) Orientation in relation to interaction partner (degrees) Observation Child and parent interviews	WT effectively measured proximity. All parents reported the WT could be helpful in assisting their child. Participants who stood too close moved into appropriate space with WT feedback.	Quantitative: Good (73%) Qualitative: Adequate (60%)
Keshav et al., (2017)	Case series	Children and adults with ASD, n=21(19 male, 2 female), 4.4-21.5 years, mean age: 11.9 (SD: 4.9) years	Brain Power Autism System (BPAS) (Google Glass Explorer Edition)	Social-emotional function	WT, clinical setting	Tolerability (care-giver report and Likert scale) Successful use and experience (Likert scale)	Majority of participants found WT tolerable when worn for 1 minute and entirety of session. Participants also reported glasses were comfortable and caregivers reported participants could use WT with assistance. Caregivers reported that participants responded more positively to the smart glasses than expected. Caregivers reported that users	Quantitative: Adequate (59%) Qualitative: Adequate (55%)

							may benefit from extended/repeated orientation to glasses.	
Kinsella et al., (2017)	Case series	Children with ASD, n=15 (10 male, 5 female), 8-16 years, mean age: 12.92 (SD: 2.33)	Google Glass and Holli app	Social function, communication	WT, clinical setting	Effectiveness: Detection accuracy, recognition accuracy Efficiency: System speed of interpreting and responding to speech and user response time to prompts. User satisfaction: Likert scale Semi-structured interview	Effectiveness: High detection and recognition accuracy indicating effective use of WT Efficiency: Response time WT robust enough to use in real time Likert scale: High comfortability Interview: High acceptability	Quantitative: Adequate (77%) Qualitative: Good (70%)
Lee et al., (2008)	case-series	Adolescent males with Asperger Syndrome, n=4	Hat mounted wireless camera Wristband skin conductance sensor	Social function, communication	CU, clinical setting	Face contact data (positive, negative detection rates) Observation Interview/ conversation	Variability in detection of faces using head-mounted camera. System may work in conversational setting, but it requires a fixed, stable environment.	Quantitative: Limited (27%) Qualitative: Limited (25%)
Liu et al., (2017)	Case series	Males with ASD, n=2, aged 8.6 years and 9.75 years	Brain power system (smart glasses)	Social function, emotion recognition	WT, clinical setting	Caregiver report (semi-structured interview) Aberrant behavior checklist	Caregivers reported participants had high to very high level of engagement, level of tolerability, level of enjoyment, ease of use and interaction with WT. Caregivers reported improved verbal and non-verbal communication, eye contact and social engagement. No change in verbal communication reported. One caregiver reported improvement in emotional connection and behavioral control while the other caregiver reported that both these areas were diminished. Both participants had reduced symptoms on aberrant behavior checklist following WT use.	Quantitative: Adequate (59%) Qualitative: Adequate (50%)
Ness et al., 2017	Case-control	Child and adolescents with and without ASD. ASD: n=29 (25 male, 4 female), mean age: 10.1 (SD:5.2) TD: n=6 (3 male, 2 female), mean age 10.0 (SD: 2.83)	JAKE Biosensor Array of continous and perioic sensors: child daytime sensor (Q™ Sensor), child nighttime sensor (AMI Micro Motionlogger Sleep Watch), B-Alert®	Everyday participation Sleep	Database (Janssen Research Data Warehouse), naturalistic (sleep), clinical setting	EDA and actigraphy, ECG and EEG (eye tracking also used but not WT). Experience with JAKE system (not linked to WT), safety, validity and reliability of data	Adverse events limited and were not related to the JAKE system. Q sensor not used as no longer commercially available. B-Alert (EEG) could not reach adequate impendence levels and difficulty with wireless. However, EDA sensor used 30 mins prior to clinical task battery. AMI	Quantitative Adequate (67%) Qualitative Limited (45%)

			X24 (EEG), CamNTech Actiwave (ECG)				Motionlogger Sleep watch able to provide reliable and valid data.	
Suzuki et al., (2016)	Case series	Children with ASD, n=6 (5 male, 1 female), 5-8 years Session 1: Children with ASD, n=10 (8 male, 2 female) Session 2: Children with ASD, n=7 (4 male, 3 female), 5 -8 years	EnhancedTouch worn on wrist	Social function, non-verbal communication	Tablet, naturalistic setting (club)	Touch events, reaction to device (observation), (frequency, duration and partner) Observation	WT accepted by participants and children were interested in device. Device capable of accurately measuring touch events. Visual feedback from device increased touch events.	Quantitative: Adequate (59%) Qualitative: Adequate (55%)
Torrado et al., (2017)	Case series	Male children with ASD, n=2, 10 years	LG Watch Urbane Smartwatches	Emotional regulation	WT, smartphone, naturalistic setting (classroom)	HR (bpm), Observation	Long duration (9 x 4-hour sessions) wearing of the device was well tolerated. Children enjoyed wearing the watch and observations suggest that strategies provided by the watch support self-regulation. WT able to detect changes in HR in real time. Measurement was confounded by states other than stress (e.g. excitement).	Adequate 65%
Qualitative								
Marcu et al., (2012)	Case series	Children and adolescents with ASD (and their mothers), n=5, 10-15 years	SenseCam (digital camera) worn around the neck iPod Touch (LifeLapse app) worn around the neck	Everyday participation	WT, PC, naturalistic setting (various)	Interviews with parents Observation	WT facilitated parents' understanding of child's experiences and needs. Parental concerns regarding the appearance of the device.	Adequate (65%)
Spiel et al., (2016)	Case study	Child with ASD, n=1, 6 years.	ThinkM (Headband with camera and pulse sensor)	Social function, emotional regulation	CU, clinical setting	Informal discussion/ collaboration	Child expressed wish for technology to retain information of perceived negative behaviors. WT useful in assessing arousal (pulse) and reviewing social situations.	Adequate (60%)
Sahin et al., (2018a)	Case series	Children and adults with ASD, n=18 (16 male, 2 female), 4.4 -21.5 years, mean age: 21.2 (SD:5.2) years	Brain Power Autism System (BPAS) (smart glasses)	Social function, emotion recognition	WT, clinical setting	Structured interviews	Majority of participants tolerated wearing glasses for at least 1minute (n=2 who did not tolerate were non-verbal). Three cases of mild adverse effects reported by 2 users including dizziness, one case of eye strain, and one instance of initial nasal bridge discomfort. Some reported glasses were warm.	Adequate (65%)

Sahin et al., (2018b)	Case series	Children with ASD, n=8 (7 male, 1 female), 6.7 – 17.2 years, mean age: 11.7 years (SD: 3.3)	Brain Power Autism System (BPAS) (smart glasses)	Social function, emotion recognition	WT, clinical setting	Semi-structured interviews	Children did not experience stress or sensory overload when using WT. Children reporting willingness to use WT at home and school. Caregivers reported that the experience was fun for their child and was successful.	Adequate (60%)
Voss et al., (2016)	Case series	Families of children with ASD, n=12, 4-17 years	SuperPower Glass (smart glasses)	Social function, emotion recognition	WT, smart phone, clinical and naturalistic setting (home)	Observation of video footage Interviews	Parents reported increased eye contacted in children with ASD. Participants enjoyed the activities. Participants stopped wearing the glasses if they became too warm. Optimal feedback mechanisms appeared to be a combination of audio and visual feedback.	Adequate (60%)
Washington et al., (2016)	Case-control	ASD and TD children and adolescents n=40 (20 ASD, 20 TD), 6-17 years	Smart glasses	Social function, emotional recognition	WT, smartphone, clinical and naturalistic settings (home)	Observation Informal interview Emotion recognition accuracy	Children responded well to wearing WT. Children responded well to the images and enjoyed the gamified activities and feedback mechanisms. Children responded better to audio feedback than to visual feedback. Majority of children chose audio cues over their own intuition. WT was uncomfortable when worn for long periods of time.	Adequate (55%)

Notes. ASD: Autism Spectrum Disorder; SMM: Stereotypical Motor Movement or self-stimulatory movement; PC: Personal computer; EEG: Electroencephalography; ECG: Electrocardiography; WT: Wearable Technology; CU:Central/Control/Base Unit; HR: Heart Rate; HRV: Heart Rate Variability; RSA: Respiratory Sinus Arrhythmia; TD: Typically Developing; EMG: Electromyography; PDD: Pervasive Developmental Disorder; EDA: Electrodermal activity

TABLE 2. Summary of purpose of WT and ICF codes

Article	WT	Purpose			ICF Codes		
		Basic Research	Intervention (WT is Intervention)	Intervention (WT supports Intervention)	Function measured	Function target	Context
Albinali et al., (2012)	Accelerometer	X		X (future)	b7563	b7563	d8201, e325, e330, e360, e5853
Billeci et al., (2016)	Enobio Headset and ECG Chest belt			X (Monitoring during intervention)	EEG (NC), b410	b1403	d880, d130, e355, e5800
Billeci et al., (2018)	ECG Chest belt	X			b410	b1403	d110, e360
Daniels et al., (2018a)	SuperPower Glass System (smart glasses)		X		d3150	d3150, b122, d1600	e310, e1301
Daniels et al., (2018b)	SuperPower Glass System (smart glasses)		X		d3150	d3150, b122, d1600	e125, e360
Di Palma et al., (2017)	ECG Chest belt			X (Monitoring during intervention)	b410	b1403, b1251	d130, d8803 e355, e5800
Funahashi et al., (2014)	EMG			X (Monitoring during intervention)	b7300	b1521, b1250, b1251, d335, d2502	d880, e310, e355, e580, e350
Goodwin et al., (2014)	Accelerometer	X		X (future)	b7653	b7653	d8201, e325, e330, e360, e5853
Hachisu et al., (2018)	FaceLooks Smart headband	X	X (future)		b140	d1600	d550, d9200, d8201 e325, e330, e360, e5853
Hirokawa et al., (2016)	EMG			X (Monitoring during intervention)	b7300, d335	b1521, b1250, b1251	d880, e3101, e355
Jiang et al., (2016)	ProCom chest worn proximity sensor)	X	X (future)		d7204	d7204	e360, e130, e1301
Keshav et al., (2017)	Brain Power Autism System (smart glasses)		X		b2152, d3150	d3150, d1600	e310, e1301
Kinsella et al (2017)	Google Glass and Holli App		X		b3100	d3501	e360, e1251
Lee et al., (2008)	Hat Mounted Wireless Camera and Wristband skin conductance sensor	X			b830, b140	d1600, b1251, b1521, d3503	d3503, e310, e360
Liu et al., (2017)	Brain Power System		X		b2152	d3150, d1600, d2501	e310, e1301

Magrelli et al., (2013)	WearCam	X			b2152	d1600	d8803, e360
Magrelli et al., (2014)	WearCam	X			b2152	d1600	d8803, e360
Marcu et al., (2012)	SenseCam		X		Everyday participation (NC)	Everyday participation (NC)	e310
Mazzei et al.,	Hatcam and sensorised shirt		X		b2152, b830, b4400	b1520, b1521, d1600	e1301, e355
Min et al., (2009)	Accelerometer	X		X (future)	b7653	b7653	Home (ND)
Min et al., (2010)	Accelerometer	X		X (future)	b7653	b7653, b1521, d2401	Therapy and home (ND)
Min et al., (2011)	Accelerometer	X		X (future)	b7653	b7653, b1521, d2401	Therapy and home (ND)
Ness et al., (2017)	Biosensor array	X			b1344, b830, EEG (ND), b410	b1340, b1341, b1342, b1343, b1521, b140	d570, d1600, e310, e360, e115, everyday participation (ND)=
Rad et al., (2016)	Accelerometer	X		X (future)	b7653	b7653	d8201, e325, e330, e360, e5853
Sahin et al., (2018a)	Brain Power System (smart glasses)		X		b2152, d3150	d3150, d1600, d2501	e310, e1301
Sahin et al (2018b)	Brain Power System (smart glasses)		X		b2152, d3150	d3150, d1600, d2501	e310, e1301
Speil et al., (2016)	ThinkM headband		X		b140, b410	d2502, b1521	e360
Suzuki et al., (2016)	EnhancedTouch		X		b265	d1201, d7105	d9100, d9201, e325, e330, e355
Takahashi et al., (2016)	SmartClothe with ECG sensor			X (Monitoring during intervention)	b410	b1521	d4454, d110, d130, d880, d115, d166, d330, e355, e310
Torrado et al., (2017)	LG Urbane Smartwatch		X		b410	b1521	d8201, d9201, e310, e330, e1151, e325
Vahabzadeh et al., (2017)	Empowered Brain System		X		b2152, d3150	ADHD symptoms (HC)	e310, e1301
Voss et al (2016)	SuperPower Glass		X		d3150	d3150, b122, d1600	e310, e1301
Washington et al (2016)	Smart glasses		X		d3150	d3150, b122, d1600	e310, e1301

Note. Studies reporting on the development of wearable technologies for the purposes of future intervention are noted as 'X (future)'

Types of wearable technologies

WTs were grouped into three categories: 1) head-mounted technologies, 2) body-worn technologies, and 3) accessory and clothing-based technologies.

Head-mounted technologies. A range of head-mounted technologies were described, including glasses or devices worn in the form of a headband or fitted hat/cap. These WTs were used to capture data such as head orientation, gaze patterns, pulse and electroencephalography (EEG).

Smart or assistive reality glasses were discussed by 10 studies (Table 1). These glasses typically had an outward facing camera capturing the faces of others, and an inward facing tracker monitoring the wearer's eye gaze patterns and were capable of providing youth with real-time feedback on their social function through providing audio or visual feedback. Several systems utilizing smart glass technology were presented as a means to support and improve social communication and interaction in autistic youth. The Brain Power System (31), Brain Power Autism System (32-34) and the Empowered Brain (formerly Brain Power Autism System) (32) used smart glasses as a social communication aid for autistic individuals, providing personalized coaching on gaze behavior and emotion recognition through gamified interaction. The SuperPower Glass system (35, 36), was also designed to support emotion recognition in autistic children through using machine learning software and automatic facial expression recognition capabilities. Similarly, Washington et al. (37) describe a system using automatic facial emotion recognition to support emotion recognition in autistic children, finding that autistic children tended to choose cues provided by the google glasses over their own intuition. While these various smart glass-based systems provide some evidence suggesting that they may improve social engagement (31), eye contact (31, 37), non-verbal communication (31), and emotion recognition (35, 38) in autistic individuals, and may reduce attention deficit hyperactivity disorder symptoms (31, 39), and autistic-like traits (35), these results are inconsistently observed, and are insufficient to draw conclusions regarding the effectiveness of these systems.

One study utilized the onboard microphone of the Google Glass and Google Speech Recognition software to develop the Holli application (40). This application 'listened' to conversations and generating conversation prompts and responses visually displayed through the glasses (40). Though preliminary and limited, this system may be useable and effective for supporting communication among autistic children.

Overall, studies investigating smart glasses suggested that they were generally tolerated by autistic youth (31-35), and were perceived as useable (31, 32, 35, 37, 40) and enjoyable (31, 33, 37, 40). Some studies, however, reported that smart glasses may become uncomfortable if worn for long periods of time, or become too warm (34, 37). When examining the potential for negative effects, evidence was found suggesting that a small number of participants experienced mild adverse effects including dizziness, nose-bridge discomfort and eye strain (34).

Other head-mounted technologies capable of measuring eye gaze were discussed (41-43) such as 'HATCAM', a headband or hat with an attached camera and mirror, used to examine visual attention to a robotic face during adaptive therapy aimed at improving social communication in autistic children (43). A similar device, the 'WearCam', using two cameras and a mirror attached to an elastic headband, provided researchers with a means to examine gaze behavior during complex social interaction (41, 42).

While not tracking eyes directly, a similar concept was employed by Spiel et al. (44), who discussed the 'ThinkM', a wearable headset with a pulse sensor and JPEG camera located at the participant's eye and recorded real-time images every ten seconds. This device was developed in collaboration with an autistic child to assist in reviewing arousal and, interpreting and reviewing social situations after-the-fact, supporting social function.

Head-mounted devices to explore and quantify face-contact or orientation to another person were explored in two studies (45, 46). A prototype head-mounted device with OpenCV Face detection to track head position and determine face contact showed promise in detecting face contact during conversations in a fixed, stable environment, however, significant difficulties were noted in regard to the system's ability to accurately detect face contact and adjust to environmental factors (such as lighting) (45). Another study used a headband device, 'FaceLooks', using infrared communication to quantify mutual face gaze behavior (46). This WT contained infrared lights that changed color depending on whether face-to-face behavior was achieved. This feedback was associated with increased face-to-face orientation, with usability investigation suggesting that participants tolerated and enjoyed wearing the device for short periods of time, indicating that the device may prove useful in intervention and investigation seeking to improve social interaction. It must, however, be noted, that a limitation of the 'FaceLooks' device was that all participants were required to wear the headband for the device to function (46). Finally, two studies aimed to use wireless EEG recording devices to examine and detect neurophysiological activities unobtrusively. In one study it was shown to be effective in examining engagement in children during play-based imitation tasks, potentially providing avenues for assessing neural activity during intervention or treatment (47), however, in a later study, difficulties in wireless syncing and obtaining adequate impedance levels precluded its use in the study (30).

*Body-worn devices***.** Body-worn technologies included sensors placed on the body, such as accelerometers, electromyography sensors and chest belts or sensors. Six articles (Table 1) investigated the use of accelerometers to measure and classify stereotypical motor movements such as body rocking and flapping, with two studies also investigating accelerometers to detect self-injurious behavior (48, 49). Accelerometers were typically worn on the hands and torso, however, one study found evidence to suggest that movements such as body rocking and hand flapping may be adequately detected by a single sensor placed on the back (50). Accelerometers to detect stereotypical movement or self-injurious behavior was observed to be generally accurate (48-52), however, significant variability in individual behavior was proposed to negatively influence classification performance, with individualized and adaptive classification of stereotypical movement and self-injurious behavior still required (53). Electromyography (EMG) sensors placed on the face were discussed as a means to measure smile behavior in autistic children in two studies (54, 55). One study found that the use of facial EMG sensors during animal-assisted therapy were effective in quantifying children's emotional experiences to the therapy (54). In a later study (55), it was shown that EMG sensors placed on the face were capable of reliably detecting smile behavior in autistic children during play with a robot.

Wearable sensors to record ECG signals, to provide markers for ANS response were used by four studies (30, 47, 56, 57). Feasibility testing suggested that the use of chest-belts to measure ECG in semi-naturalistic paradigms and clinical is effective, and may enable real-time tracking of engagement (47, 56) and autonomic nervous system activity (30, 57). Another chest-worn sensor was the 'ProCom', a proximity sensor developed using parallel design with autistic children and adults to support awareness of interpersonal space. Despite some limitations, including children's tolerability of the device and comfort, the device effectively measured proximity, was useable in everyday life, and resulted in autistic children modifying their proximity to others appropriately (58).

Accessory and clothing-based technologies. Accessory and clothing based technology included wrist-worn devices (14, 30, 45, 59), sensorised shirts, (43, 60) and technology worn around the neck (61).

Wrist-worn devices were examined in four studies (Table 1). These devices measured physiological signals including skin conductance (45), touch (59), and heart rate (14). One study also used the AMI MotionLogger Sleep Watch to measure sleep onset, quality, and duration (30), while this study also aimed to use a child daytime sensor measure electrodermal activity (EDA), actigraphy, and skin temperature, this daytime sensor was discontinued prior to the study with EDA instead measured using dry electrodes in a clinical setting.

In addition to the head-mounted wearable camera device, Lee et al. (45) reported the use of a bracelet to measure skin conductance levels to provide an index of arousal during social and physical engagement. This study showed that skin conductance levels among autistic participants varied in accordance with the conversation topic and whether that topic was of interest, indicating that skin conductance measured through a wrist device may provide a means to examine physiological information during social interaction. An 'LG Watch Urbane' smartwatch was similarly used to enable autistic children to self-regulate their emotions (14). Through measuring heart rate, the smartwatch was capable of detecting anger or distress in real time, with self-regulation strategies developed by parents and teachers displayed through the smartwatch. Observations with two children over nine days showed this device was used and enjoyed by the children, with preliminary evidence suggesting that the device may assist children to self-regulate emotion in the classroom. The wrist device described by Suzuki et al. (59) was developed as a means to measure and encourage physical contact or touch in autistic children. The 'EnhancedTouch' was capable of quantifying touch events between two individuals, including frequency and duration of touch and provided visual feedback through emitting light when touch events occurred. While this device was capable of measuring only hand-to-hand touch, it was found to be effective in measuring touch events, was accepted by children, and increased instances of touch when visual feedback was provided (59).

Two studies discussed the use of sensorised shirts as a wearable platform to assess physiological and/or electrocardiographic (ECG) signals. A 'Smart Clothe' which contained ECG sensors in the wrist cuffs of a long-sleeved garment worn by children was shown to provide a reliable means for parents and therapists to monitor mental stress during therapy in children (60). A similar wearable garment with sensors woven into the fabric was capable of capturing a range of physiological activities including heart rate, heart rate variability, respiratory rate, skin temperature, and skin conductance during the course of therapy using robots (43).

One study, through consultation with parents of autistic children, used two devices, the 'SenseCam' a wearable digital camera worn around the neck and a modified iPod Touch with the Lifelapse application, also worn around the next, were used to capture still images from the wearer's perspective. The 'SenseCam' automatically captured images every one minute, increasing in frequency if changes were detected, while the modified iPod Touch automatically captured images every 30 seconds. These devices both improved understanding of their child's experiences and needs, and enabled parents and autistic children to review interactions. Concerns were however raised by participants regarding the appearance of the device, which was suggested to be lacking in social accessibility and parents reported difficulty accessing data collected by the devices (61).

Mapping to the ICF framework

A total of 202 meaningful concepts were extracted from the articles. Of these concepts, 47 related to the functions measured by the WTs (e.g., heart rate), 60 concepts related to the functions targeted by the WTs (purpose of WT, for example, stress management), and 95 related to the context that the WTs were implemented in (e.g., in the classroom). Meaningful concepts are subsequently linked to a total of 300 codes, including 189 codes at the second level, and 111 codes at the third level. Of the second level category codes, 55 related to body functions, 65 related to activity and participation and 69 related to the environment. Only codes identified in at least 5% of the linked articles are discussed (Table 3).

Body functions. The physiological and behavioral functions measured by the WTs, as well as their functional targets, were linked to the body function domain. Six out of the eight body function chapters were represented, including mental functions (b1), sensory functions and pain (b2), speech and voice functions (b3), functions of the cardiovascular, hematological, immunological and respiratory systems (b4), neuromusculoskeletal and movement relation functions (b7) and functions of the skin and related structures (b8). Emotion functions (b152) were the most frequently linked code, referring to WTs aimed at supporting the monitoring and self-management of emotions (k = 10). Studies were also frequently linked to functions and structures adjoining the eye (b215), which included devices that measured gaze behavior, such as fixations or saccades (k = 8). Involuntary movement functions (b765), were linked to devices which both measured and aimed to reduce stereotypic behavior (k = 6). Seven studies measured attention functions (b140), with a further seven measuring heart functions (b410) including heart rate and pulse. Dispositions and intra-personal functions (b125) and global psychosocial functions (b122) were both linked to four devices and, referred to devices which sought to target or improve social functioning or social-cognitive responding. Chapters 5 and 6 referring to functions of the digestive, metabolic and endocrine systems, and genitourinary and reproductive functions respectively were not represented.

Activity and participation. Activity and participation codes referred to the physiological and behavioral functions measured by devices, their functional targets and the context in which the WTs were used. Eight of the nine activity and participation chapters were covered, including learning and applying knowledge (d1), general task demands (d2), communication (d3), mobility (d4), self-care (d5), interpersonal interactions and relationships (d7), major life areas (d8), and community, social and civic life (d9). The most frequently linked code was focusing attention (d160), which included devices measuring and facilitating eye contact or face-to-face behavior in autistic youth (k = 14). Communicating with receiving nonverbal messages was also commonly linked (k = 9), referring to devices measuring and facilitating the facial emotion recognition, while managing one's own behavior (d250) referred to devices seeking to support self-regulation (k = 5). Engagement in play (d880), school education (d820) and copying (d130) linked to seven, five and three devices respectively referred to the context in which devices were commonly used. Domestic life (d6) was not represented.

Environment. Environment codes were linked to the context that the WTs were used in and covered three of the five environment chapters of the ICF including products and technology (e1), supports and relationships (e3), and service systems and policies (e5). WTs were frequently used with the child's immediate family (e310) (k = 14), with other professionals (e360) including researchers or observers (k = 13) and with health professionals (e355) such as therapists (k = 7). Devices were also used with acquaintances, peers, colleagues, neighbors and community members (e325), and people in positions of authority (e330), such as teachers which were linked to six devices each. Devices were commonly linked to products and technology for education (e130), which included devices that were paired with technologies such as robots for the purposes of therapy, as well as devices that provided coaching (k = 11). Four devices were linked to education and training services (e585) and three to health services, systems and policies (e580) referring to devices used in the context of school or therapy. The natural environment and human-made changes to the environment (e2) and attitudes (e4) were not represented.

TABLE 3. Absolute and relative frequencies of studies linked to the ICF

ICF Code	ICF Descriptor	Count	Relative frequency (within ICF domain)
Body functions			
b152	Emotional functions	*10*	18%
b215	Functions of structures adjoining the eye	8	15%
b140	Attention functions	7	13%
b410	Heart functions	7	13%
b765	Involuntary movement functions	6	11%
b122	Global psychosocial functions	4	7%
b125	Dispositions and intra-personal functions	4	7%
b830	Other functions of the skin	3	5%
b730	Muscle power functions	2	4%
b134	Sleep functions	1	2%
b265	Touch function	1	2%
b310	Voice functions	1	2%
b440	Respiration functions	1	2%
Activity and participation			
d160	Focusing attention	14	22%
d315	Communicating with - receiving - nonverbal messages	9	14%
d880	Engagement in play	7	11%
d250	Managing one’s own behavior	5	8%
d820	School education	5	8%
d130	Copying	3	5%
d920	Recreation and leisure	3	5%
d110	Watching	2	3%
d240	Handling stress and other psychological demands	2	3%
d335	Producing nonverbal messages	2	3%
d350	Conversation	2	3%
d115	Listening	1	2%
d120	Other purposeful sensing	1	2%
d166	Reading	1	2%
d330	Speaking	1	2%
d440	Fine hand use	1	2%
d445	Hand and arm use	1	2%
d550	Eating	1	2%
d570	Looking after one's health	1	2%
d710	Basic interpersonal interactions	1	2%
d720	Complex interpersonal interactions	1	2%
d910	Community life	1	2%
Environment			
e310	Immediate family	14	20%
e360	Other professionals	13	19%
e130	Products and technology for education	11	16%
e355	Health professionals	7	10%
e325	Acquaintances, peers, colleagues, neighbors and community members	6	9%
e330	People in positions of authority	6	9%
e585	Education and training services	4	6%
e580	Health services, systems and policies	3	4%
e115	Products and technology for personal use in daily living	2	3%
e125	Products and technology for communication	2	3%
e350	Domesticated animals	1	1%

Discussion

A range of WTs for autistic youth, measuring and targeting a variety of functions were identified in this review. Critically, this review identified and examined an additional 31 studies not reviewed by Koumpouros and Kafazis (15), enabling extension of their findings. While cumulatively, there is promising evidence to suggest that WTs may prove useful for measuring and supporting functioning in autistic youth, it is apparent that the use of WTs is in its infancy and requires additional investigation.

The synthesis and linking of WTs to the ASD ICF Core-sets (8) and ICF-CY (16) shows that a number of physiological and behavioral functions, measured for a variety of purposes, across a range of contexts can be captured through the use of WTs. Through linking to the ASD ICF Core-sets (8) and ICF-CY (16), findings extend those presented by Koumpouros and Kafazis (15), enabling in-depth exploration of how WTs are used to measure functioning, abilities and disabilities in autistic youth. This collection of real-time physiological data during complex, everyday activity and participation enables a holistic view of an individual's functioning, essential for deepening the understanding of ASD and its impacts, as well as in understanding an individual's unique functioning profile. This is perhaps of particular importance given that the ASD ICF Core-sets emphasize the need to consider how the environment may influence an individual's functioning (8).

WTs have the capacity to enable families and clinicians to better understand an individual's needs and functioning. Typically, these needs, goals, values and interests are evaluated in the form of standardized paper-based assessments or communication exchange, which are highly reliant on a person's capacity to express their thoughts, feelings and needs verbally. This can be a key difficulty for autistic youth (13), particularly for those who may not communicate verbally, or who have greater support needs. The use of WTs may facilitate clinicians to measure and monitor the nature, quantity and quality of everyday activities of autistic youth, augmenting traditional assessment of functioning in autistic individuals (13), and may enable families to better understand the everyday experiences of their children.

WTs may also be particularly suited to intervention to support and facilitate functioning. As demonstrated by a number of studies included in this review, WTs were capable of providing therapists, researchers and parents with real-time data on a child's response to intervention and treatment (43, 47, 54-56), providing an objective and more relevant means of exploring intervention effects. Through individually measuring a child's response during the course of therapy, an intervention can be modified to address their unique needs and challenges using a precision medicine approach (62).

Some WTs were also interventions in themselves, providing real-time feedback on functioning, for example, many of the smart glasses discussed provided real-time feedback to support social communication (35, 37), smart watches provide self-regulatory strategies (14) or sensors to guide proximity to others (58). Through enabling autistic youth to visually map their own emotions, bodily signals of stress and social interactions, they may be better supported to interpret and understand how to cope, communicate and socialize effectively within a social context (63). This feedback may motivate self-management (64) and support greater independence, and work towards shifting the focus of interventions in ASD from a medical model view to a social model perspective.

In addition to their benefits in supporting or acting as interventions, WTs also have apparent advantages from a research perspective, providing an objective, and arguably, more ecologically valid means of exploring the mechanisms underlying functioning in autistic youth. Given the heterogeneous nature of ASD, WTs may provide unique opportunities to advance the understanding of how ASD manifests both at a group and at individual level, enabling a greater understanding of the factors, which can be targeted during the course of intervention.

Roadblocks, challenges, and future directions

Despite the promising evidence for WTs, a number of significant limitations remain and must be explored. While exploring the validity, reliability, accuracy and feasibility of the WTs compared to gold-standard measures of physiological activity was beyond the scope of this review, it seems clear that additional work must be done in this area. Ensuring that WTs are valid, reliable, acceptable and feasible must be considered by future research in this area before WTs are readily adopted within both research and intervention. While internal validity, external validity, reliability and acceptability considerations are discussed here, Düking et al. (65) also provide recommendations for evaluating WTs used for physical activity which may prove useful for future WTs development to measure and support functioning in autistic youth and other populations. Using this review and the recommendations provided for other populations, guidelines and benchmarks should be developed to ensure that WTs are valid, reliable and useable for autistic youth.

Internal validity. WTs to support function are generally concerned with measuring physiological or behavioral activity and using this as an index for function. This process is however rarely a one-to-one mapping exercise, particularly for more psychologically relevant constructs, as was the case for many WTs included in this review as demonstrated by the ICF linking. With these constructs, there is a risk of affirming the consequent. For example, distress will typically result in lower heart rate variability however, if heart rate variability is observed via a WT, it may not have necessarily been preceded by increased distress.

The internal validity of WTs remains largely unknown and researchers seeking to develop WTs to measure and support physiological functioning must be cautious of this fallacy.

External validity. Assuming that devices are capable of measuring and indexing the desired functional outcome, the WTs must be generalizable to other contexts. As evidenced by the significant variability in activity, participation, and environmental ICF codes linked to the WTs, it is apparent that many studies sought to employ their WTs in ecologically valid environments and contexts. However, the external validity of nearly all the studies included in this review could be considered low due to their small sample sizes. Autistic individuals exhibit high variation and cannot be well represented by the small samples used in case-studies and case series studies, contributing to difficulty in understanding the true effectiveness and reliability of the WTs described.

Reliability. The devices must also be able to reliably collect physiological or behavioral data. As ASD is a heterogeneous condition, with its effects on functioning influenced by a number of factors, including the environment (8), it is essential that WTs are readily adaptable to variability in individual functioning. While not within the scope of this review, various physiological measurements may be derived from WTs (for example, heart rate variability, beats per minute, respiratory sinus arrhythmia), with varying levels of accuracy and reliability. The reliability of measures taken from WTs may be influenced by a number of factors, including their positioning on the body, such as in the case of electrodermal activity, which may show an asymmetric pattern of activity, resulting in different readings of arousal depending on the side of the body the measurement was taken from (66). Future research should seek to conduct thorough reliability testing of these devices (65, 67).

Acceptability. A strength of many studies was that the experiences of both the WT users and caregivers were taken into account, with some studies reporting the development of their devices in collaboration with autistic individuals themselves (44, 58). These demand and consumer-driven approaches enable developers and researchers to ensure the needs of autistic youth and their families are met. Future research should continue to seek the perspectives and experiences of autistic individuals, and their families in the design of WTs. However, a cautionary note must be made in relation to a 'one-size-fits-all' approach to wearables in ASD. This is particularly relevant given that ASD is inherently a spectrum disorder and the wide acknowledgment that each autistic person is unique, with differing behaviors and needs. It is likely that the customizability of wearables is critical in supporting their acceptability and fostering of positive functional outcomes (68).

Some studies reported that the aesthetics of devices were a concern for participants. Beyond considering the properties of weight and obtrusiveness, researchers largely failed to consider the implications of the size or appearance of the wearables within a child's everyday environment. This is of particular relevance in ASD were wearing devices that are socially obtrusive may further exacerbate social difficulties (68). Many emerging WTs are sleek and discrete, and aligned with fashion trends (i.e., smartwatches and bracelets), increasing their social desirability and acceptability, enhancing their usability and ability to empower autistic youth. Ideally, in the future wearables for autistic youth will have the capacity to sustainably address the needs of a child from functional, aesthetic, technical and cultural viewpoints (69).

While studies included in this review demonstrated that the WTs were generally tolerated and accepted by participants, few examined the impact of wearing these devices for long periods. Those that did often reported discomfort after 20-30 minutes due to heating or weight of the device (33, 34, 37), suggesting that there are still challenges to their prolonged use. Very few devices also exhibited the ability to store or process information retrieved in the WTs themselves, requiring a personal computer or a central processing unit for the individual or experimenter to access the information. Optimization of all aspects, including the aesthetics of WT is paramount to ensure that WTs are capable of meeting the needs of autistic youth.

Conclusion

WTs can enable autistic youth, their families, and researchers with the ability to measure and monitor functional outcomes associated with day to day life. Such devices have promising prospects in improving the understanding of ASD, and in supporting everyday functioning and quality of life for autistic youth and their families. Whilst the rapid development of WTs promises an exciting future in the accurate and reliable assessment of functions in autistic children and youth in ecologically valid settings, it is clear this area is still in development and requires additional investigation before WTs can be adopted by autistic youth to support function. Future research should focus on examining WTs that are discrete, consumer-driven and independent of an external computer/device for retrieval of data, to be truly "wearable".

Conflicts of interest

Dr. Bölte reports personal fees from Medice, Roche, Prima Psychiatry, Hogrefe, grants from Swedish Research Council, ALF, Hjärnfonden, Clas Groschinsky, Promobilia, Region Stockholm, FORTE, outside this work. All other authors report no conflicts of interest.

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