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Motion-based technology to support motor skills screening in developing children: A scoping review

Benoit Bossavit [a,b,*], Inmaculada Arnedillo-Sánchez [a]

[a] School of Computer Science & Statistics, Trinity College Dublin, Ireland
[b] School of Computer Science & Programming Languages, Universidad de Málaga, Spain

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ABSTRACT

Background: Acquiring motor skills is fundamental for children's development since it is linked to cognitive development. However, access to early detection of motor development delays is limited.
Aim: This review explores the use and potential of motion-based technology (MBT) as a complement to support and increase access to motor screening in developing children.
Methods: Six databases were searched following the PRISMA guidelines to search, select, and assess relevant works where MBT recognised the execution of children's motor skills.
Results: 164 studies were analysed to understand the type of MBT used, the motor skills detected, the purpose of using MBT and the age group targeted.
Conclusions: There is a gap in the literature aiming to integrate MBT in motor skills development screening and assessment processes. Depth sensors are the prevailing technology offering the largest detection range for children from age 2. Nonetheless, the motor skills detected by MBT represent about half of the motor skills usually observed to screen and assess motor development. Overall, research in this field is underexplored. The use of multimodal approaches, combining various motion-based sensors, may support professionals in the health domain and increase access to early detection programmes.

Introduction

Throughout life, humans learn to use their muscles to perform motor skills. During childhood, typically developing (TD) children usually acquire the same skills at similar ages. Acquiring motor skills during childhood is fundamental for children's development because it is associated with their cognitive and learning development. Some cognitive skills originate in the prontal cortex and the cerebellum, which are also activated with the execution of motor skills [44,85]. Furthermore, cerebellum dysfunction is usually associated with (neuro)developmental disorders such as autism [47,124], speech disorders such as dyslexia [180] or learning disorders such as Developmental Coordination Disorder (DCD) [144].

Theore, detecting potential delays in motor development is paramount. Currently, initial concerns regarding developmental delays are commonly raised by parents observing problems with daily activities or teachers noticing challenges with motor activities at school [117]. The American Academy of Paediatrics [141] recommends an early detection programme for developmental delays leading to early interventions positively impacting children's development [18] that could also redirect developmental trajectories and focus attention on tasks and sensory-motor performance [34,50,126]. In addition, it would support social and emotional development within the family circle [139], which can reduce the risk of health-related psychosocial complications [122]. However, inaction on early detection leads to delayed interventions, poor communication with the family [193] and performance at school [147], and risk of poor outcomes in the life course [143,187].

Despite the benefits of early detection, only an insignificant percentage of the population avails of it [119] due to its associated costs. Early detection programmes require engagement with trained professionals over several sessions and rely on access to limited specialist centres or adequately staffed services [42,57]. Therapists' time and specific materials and activities make children's monitoring expensive [155]. Additionally, cultural background, language barrier, low income, insurance issues, and lack of information hinder access to these services [187].

This scoping review adopts a multidisciplinary approach to search for technological complements that may support and increase access to

* Corresponding author at: School of Computer Science & Statistics, Trinity College Dublin, Ireland.
E-mail address: benoit.bossavit@uma.es (B. Bossavit).

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early detection of motor developmental delay by screening motor skills' execution from an early stage. The field of Human-Computer Interaction (HCI) has made much progress with sensors able to capture and detect human movements through intuitive interaction with digital applications based on body motion. The combination of sensors and algorithms that can recognise human movement patterns is called Motion-Based Technology (MBT). Previous Systematic Literature Reviews (SLR) have explored MBT as a tool to increase physical activity [128,130,142,152] and support children's therapy [67,87,125,149]. However, it remains unclear which, for what purpose, and how MBT may be relevant to screen motor skills in developing children to identify potential motor developmental delays. To this end, this review examines the literature through the lens of four research questions:

- RQ1: What type of MBT is being used to detect children's motor skills?
- RQ2: What motor skills are being detected with MBT?
- RQ3: For what purpose is MBT being used?
- RQ4: What motor development phases are being targeted by MBT?

These four RQs will inform the discussion regarding the relevance and potential of MBT to support and increase access to motor skills screening in developing children at an early stage.

Methods

Search strategy

Up to December 2020, with no domain and no year restrictions, a search was conducted on the following databases: *Scopus, SpringerLink, ACM Digital Library, IEEE Xplore, PubMed*, and *Web of Science*. Details of the search strings are shown in Table I.

Eligibility criteria

To be included in this review, the publications had to: (1) involve participants under 18 years of age, (2) use MBT to detect movements or gestures, (3) conduct an evaluation study (studies focused on design guidelines only were excluded), (4) be written in English and (5) have the full-text available online or in the university's library.

Search results

This scoping review was conducted following the PRISMA statement, and its flow diagram is illustrated in Fig. 1. Besides the database search, the studies erenced in previous relevant SLRs were integrated individually into our list of works to review. Duplicated documents were removed, and the preliminary selection of works was obtained by reading the titles and the abstracts. Full papers were selected, observing the eligibility criteria. Finally, 164 full texts were analysed and classified using the following categories: 1. erence; 2. year; 3. purpose (screening, assessment, intervention); 4. name of system; 5. device (depth sensor, IMU, etc.); 6. motor skill (fine or gross); 7. the number of participants; 8. participants' age; 9. type of participants (typically developing, autism, cerebral palsy, etc.); 10. number of sessions; 11. duration of the sessions; 12. design method (non-experimental, quasi-experimental, experimental); 13. instrument (survey, standard framework, etc.); 14. main outcomes. Due to the number of erences, the main characteristics of the selected studies are accessible in Appendix A.

Table I
Search strings.

Scope	String
Technology	("Motion-based" OR "gesture-based) AND
Motor skills	("motor skill" OR "locomotor" OR "balance" OR "stability" OR "stationary" OR "manipulati*") AND
Population	("child*" OR "adolescent" OR "teen*" AND NOT "adult")
MesH terms for PubMed	("Exercise"[Mesh] OR "Child Development"[Mesh] OR "Motor Skills"[Mesh])

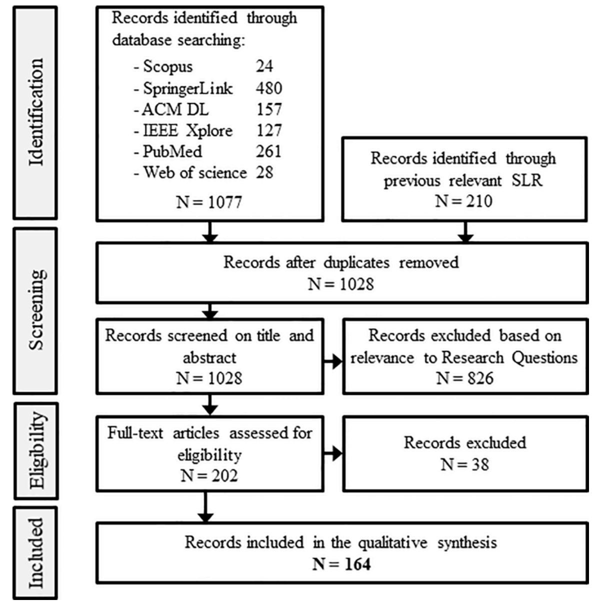

Fig. 1. PRISMA flow diagram.

Results

RQ1: Type of MBT used to detect children's motor skills

MBT avails of sensors to capture motion data. The analysis of the studies in this review identified several types of sensors used to study children's motion. They were classified into the following 6 clusters:

- *Inertial Measurement Unit (IMU)*: accelerometers and gyroscopes that detect the angular variation and acceleration in movement. For instance, the Nintendo Wiimote.
- *Depth sensor*: depth cameras that map the scene and provide 3D positions of humans' joints. For example, the Microsoft Kinect and the Leap Motion.
- *Marker-based*: sensors placed on the human body, which are tracked by a set of high-resolution cameras to provide accurate 3D positions of the human's joints. Such as the Vicon system.
- *Camera*: video cameras that record the coloured scene and provide 2D information about the human body. For instance, the Playstation Eye.
- *Pressure mat*: mats with force-plate cells that measure pressure and force. Their accuracy depends on the density of the cells. For example, the Wii Balanceboard and Dance Dance Revolution mat.
- *Others*: touchscreens; goniometers and bending sensors, which capture angles' data and are usually embedded in clothing such as gloves; dynamometers, such as mechanical arms that retrieve haptic information such as force, torque and power; and robots, amongst others.

Fig. 2 illustrates the use of these MBTs over the last few years. As shown in the timeline (Fig. 2), research intensifies with the release of commercial sensors. The first works examining the potential of *IMUs* and *Pressure mats*, which sustained the research community's interest for almost a decade, emerged with the release of the Nintendo Wii and Wii

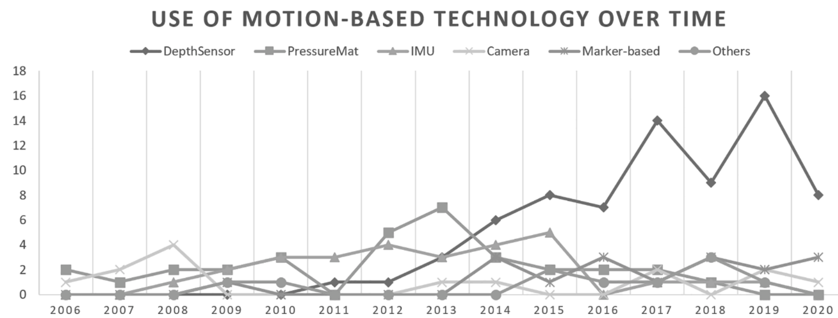

Fig. 2. Distribution of studies over time according to motion sensor used.

Table II
developmental motor skills developed during the *rudimentary* and *fundamental* phases identified in PDMS-2 [59], M-ABC2 [86], TGMD-2 [188] and BOT-2 [25].

Type		Dev. Phase	Motor skill	Device	Nb	
					CG	PS
Gross Motor Skills	Stationary	Rudimentary	Hold / turn head			
		Rudimentary	Sit	Other (cushion)		1
		Rudimentary	Stand up	DS		1
		Rudimentary	Kneel			
		Rudimentary	Squat	DS	6	1
		Fundamental	Imitate movement	DS	3	3
		Fundamental	Stand on tiptoe			
		Fundamental	Stand one leg	PM	16	
		Fundamental	Touching opposite foot			
		Fundamental	Sit-up / Push-ups			
	Locomotor	Rudimentary	Wiggle / Squirm			
		Rudimentary	Roll over			
		Rudimentary	Crawl / scoot / cruise			
		Rudimentary	Step / walk	DS / IMU	33	3
		Fundamental	Walk on tiptoe			
		Fundamental	Climb/Walk up/down steps			
		Fundamental	Walk line heel-toe			
		Fundamental	Run	DS / IMU / Camera	33	3
		Fundamental	Jump forward	DS / Camera		3
		Fundamental	Jump up / hurdles	DS / trampoline	19	5
		Fundamental	Jump down			
		Fundamental	Walk sideways	DS / PM / Camera	20	
		Fundamental	Walk tiptoe			
		Fundamental	Jump sideways	DS		1
		Fundamental	Pedal	Other (Bike)		2
		Fundamental	Hop	DS / Camera		3
		Fundamental	Skip	Camera		1
		Fundamental	Gallop	DS / Camera		2
		Fundamental	Roll forward			
	Manipulative	Rudimentary	Push / pull	Other (Robot)		1
		Rudi / Fund	Kick a ball	Camera		1
		Fundamental	Dress / Undress			
		Fundamental	Throw an object	Camera		1
		Fundamental	Catch an object	Camera		1
		Fundamental	Clap hands with rhythm			
Fine motor skills	Manipulative	Rudimentary	Grasp fingers	DS / Others		3
		Rudimentary	Touch face / mouth	DS		1
		Rudimentary	Hold toys	Other (FutureCube)		1
		Rudimentary	Turn page			
		Rudimentary	Drink from cup			
		Rudimentary	Eat with spoon			
		Rudi / Fund	Pour			
		Rudi / Fund	Hold pencil			
		Rudi / Fund	Build tower	Other (FutureCube)		1
		Rudi / Fund	Turn doorknob / screw lids			
		Rudi / Fund	String small items			
		Rudi / Fund	Draw a trail	DS / Camera / Other		3
		Rudi / Fund	Placing coins / pegs	DS / Camera		4
		Fundamental	Thread a lace	DS / Camera		1
		Fundamental	Build bridge/pyramid			
		Fundamental	Touch body parts	DS		2
		Fundamental	Cut			
		Fundamental	Copy figures			
		Fundamental	Draw	DS		2
		Fundamental	Write			

Dev: Development; DS: Depth sensor; PM: Pressure mat; NB: Number of studies; CG: Commercial games; PS: Personalised solutions.

Balanceboard (2008). Two years later, with the release of the Microsoft Kinect (2011), the number of publications reporting the use of *Depth sensors* experienced a solid increase, and they became the most popular MBT to study children's motion. Microsoft's decision to release access to the Kinect sensor meta-data: the 3D position of the users' skeleton, significantly contributed to the adoption of this technology in the field because it eased the development of personalised software and opened novel research opportunities to develop customised digital tools.

RQ2: Motor skills detected by MBT

This section analyses the motor skills detected by MBT in the 164 studies analysed. To understand the relevant skills in motor development, we identified the skills used to assess motor functioning in children (Table II) [25,59,86,188].

Most of the studies, 75 out of 164, made use of the following 8 commercial motion games: *Kinect Adventure* [51,89,115,138,163,204], *Wii-fit* [5,8,19,53,55,76,84,100,135,158,159,166,173,175,184,186], *Eyepet* [89], *Eyeplay* [9,98,108,120,129,140,168,182], Wii sport [2,38, 45,49,64,66,77,78,80,107,118,133,151,153,156,167,170,174,192,196, 197,199], *Kinect sport* [12,28,29,48,66,75,96,116,162,181,190], *Dance Dance Revolution* [2,11,37,54,58,65,78,108,121,123,148,172,173,189] and *Kinems* [104,105,161].

These commercial games detected 7 gross motor skills identified as developmental motor skills (Table II). Of these, 4 were stationary skills: *standing up* (Kinect adventure, Kinect sport, Kinems); *squatting* (Kinect adventure); *imitating movement* (Kinems) and *standing on one leg* (Wii-fit); and 3 were locomotor skills: *running* (Kinect adventure, Kinect sport, Wii-fit); *jumping up* (Kinect adventures, Kinect sport, Kinems), and *walking sideways* (Kinect adventures, Dance Dance Revolution). However, it is fundamental to highlight that commercial games are not aimed at analysing the performance or correct execution of motor skills by developing children. The detection is approximate since the aim of these games is to entertain a broad audience of all ages. The above-mentioned commercial games were used to detect other motor skills such as *change of body position* (Kinect adventure, Kinect sport, Kinems, EyePlay), *arm movement* (Kinect adventure, Kinect sport, Kinems, Wii-fit, Wii-sport, EyePet) and *hand rotation* (EyePet). However, the assessment frameworks do not define these three skills sets as developmental motor skills, and the studies involving them are not relevant to motor development screening.

Using personalised solutions accounted for 72 studies, of which 28 detected developmental motor skills. There were 7 studies focused on stationary skills which recognised users' sway movement while *sitting* [191] and *standing* [16], *squatting* [127], and *imitating a posture* [13,70, 154,194]. Another 7 studies looked at locomotor skills: *jogging* [22,102, 183], *jumping (forward/up/sideways)* [22,102,110,127,183], *pedalling* with an indoor bike [1,82], *hopping* [22,102,183], *skipping* [183], and *galloping* [102,183]. There were 2 studies focused on gross manipulative skills: *push* or *pull* [56] and *kick, catch, strike*, and *throw objects* [183]. Another 12 studies detected fine developmental motor skills: *pinching and grasping fingers* [20,165,203], *placing their hand on the face* [99], *holding a toy* [134], *building a tower* [134], *drawing a trail* [3,111,203], *placing pegs* [26,27,111,185], *threading lace* [111], *touching specific parts of the body* [23,24] and *drawing* [7,32]. The remaining 44 studies focused on detecting skills which are not considered developmental motor skills, such as *Arm movement* [4,6,14,15,33,35,39,41,68,74,81,88,90,91,92, 106,109,131,137,138,145,146,160,164,171,179,195], *body position* [39,40,41,43,71,79,90,91,137,164,169,195] and *hand rotation* [30,52, 69,83,94,95,103,112,136,150,157,202].

The last 17 studies used *marker-based* technology to analyse body kinematics while children were *walking* [10,31,36,46,62,63,72,93,97, 113,132,198], *performing dual tasks* [73], *stationary exercises* [200,201] or *using hand tools* [60,101]. These studies detected the range of motion, rotation and angular velocity of body joints but were not aimed at recognising specific motor skills.

RQ3: Purpose for the use of MBT

A typical process to evaluate motor development, and identify potential delays, encompasses 3 phases: *Screening; Assessment*; and *Intervention* [17]. To keep the analogy with this process, we categorised the studies according to the purpose for using MBT:

- *Screening*: detects the capacity for execution of specific motor skills
- *Assessment*: supports professionals in diagnosing potential developmental delays/conditions
- *Intervention*: either treats or trains users through the execution of specific skills. This category encompassed 3 subcategories according to the objective of the intervention:
  - *Fitness*: motivates and supports participants to do physical activity. Participants in these studies were not necessarily assessed for impairments or underlying conditions. Two further sub-groups were identified in the *Fitness* cluster:
    - *Well-being*: incorporates studies aimed at improving fitness levels and energy expenditure.
    - *Physical Education*: includes studies aimed at integrating MBT in school PE lessons.
  - *Therapy*: supports therapies for children diagnosed as non-typically developing. This cluster is divided into two further sub-groups according to the aim of the therapy:
    - *Physical*: encompasses studies aimed at working on specific motor skills
    - *Cognitive*: includes studies aimed at working on cognitive skills
  - *Training*: teaches, trains, or improves specific skills. This cluster is divided into two further sub-groups according to the training's objective:
    - *Physical*: incorporates studies focusing on motor skills

Cognitive: includes studies focusing on cognitive skills

A fourth category is added, which is called **HCI**, where the purpose of the studies is to provide guidelines for the use or development of MBT.

HCI

Out of 164 studies, 3 evaluated the interaction of MBT to provide guidelines for the HCI community [13,136,164]. 1 study developed a protocol to recognise jumps and sidesteps while children play the Kinect Adventure game [163].

Screening

Of 164 studies, 23 fell into the screening category, amongst which 19 aimed to cluster motor differences. There were 14 studies which measured the differences in body kinematics between TD children and children with cerebral palsy [31,46,62,63,93,132], overweight [72,200, 201], down syndrome [36,113], scoliosis [198], hearing loss [10] or Williams syndrome [97]. Another 3 studies aimed to cluster kinematics differences of TD children manipulating different objects [60,101] or performing dual tasks [73]. Additionally, 2 studies observed the quality of movement patterns between TD and children with DCD [75,178].

The remaining 4 studies aimed at screening the execution of specific motor skills such as *grasping* and *building tower* skills with TD children aged 7-9 years [134]; stereotypical gestures (hand in the face, hand flapping, hand behind back, body rocking, fingers flapping) in children with ASD aged between 5 and 10 years [99]; *jumping, hopping* and *jogging* with TD children aged 8 to 12 years [21]; *run, gallop, jump forward, slide, hop, skip, kick, catch, strike, throw up/down* and dribble with TD children aged 4-6 years [183].

Assessment

Out of the 164 studies, 3 aimed to support the assessment of motor or cognitive functioning in children by contrasting the results with assessment frameworks. Of these, 1 study assessed fine motor skills (*placing pegs, threading lace* and *drawing trails* tasks) [111] with children with and without DCD between 7 and 10 years using the assessment tool MABC-2 [86]. Another study assessed locomotor skills (*jogging, jumping, hopping* and *galloping*) [102] with TD children aged 3 to 8 years using the assessment tool TGMD-2 [188]. The last study assessed learning disability [35] of children aged 7 to 11 years using a personalised solution interacting with arm movements.

Intervention

The *Intervention* category was by far the largest, with 134 studies representing about 82% of the studies included in this review. *Therapy* was the most prolific by subcategories, with 68 studies, followed by *Fitness* with 43, and *Training* with 23.

Further analysis highlights that within the *Therapy* cluster, MBT is predominantly used to support *physical therapy* with 53 studies [3,4,5,8,9,15,16,19,20,27,28,29,33,38,40,51,52,53,55,68,77,84,88,92,96,98,100,103,104,115,116,135,146,154,158,159,160,165,166,167,168,170,174,175,179,181,184,185,186,191,199,203,204]. In contrast, there were only 15 studies in the *cognitive therapy* category [7,12,30,32,41,69,70,81,138,157,161,169,171,194,202]. In terms of the *Fitness* cluster, 29 studies fell in the *well-being* group [1,37,54,56,76,78,79,80,82,89,107,108,110,118,120,121,123,127,129,131,140,148,151,153,162,182,189,196,197], and 14 studies in the *physical education* [2,11,45,48,49,58,64,65,66,133,156,172,192,195]. Finally, the *Training* cluster consisted of 5 studies in the *physical* skills training group [26,43,71,173,190] and 18 in the *cognitive* one [6,14,23,24,39,74,83,90,91,94,95,105,106,109,112,137,145,150].

RQ4: Motor development phases targeted by MBT

Motor development is defined by the *lexive* (in-utero to 1 year), *Rudimentary* (1 to 2 years), *Fundamental* (2 to 7 years) and *Specialised* (7+ years) developmental phases [61]. While during the *lexive* (in-utero – 1 year) phase, children perform involuntary movements, which turn into voluntary movements in the *Rudimentary* (1-2 years) phase, it is in the *Fundamental* (2-7 years) phase when they develop basic motor skills. Once acquired, they become building blocks for children to develop more complex movement patterns during the *Specialised* (7+ years) phase when children learn to combine basic motor skills for more complex purposes and enter a lifelong utilisation stage [61]. The development of motor skills is progressive and improves with age [176]. Although fine and gross motor skills develop independently [176], once these are acquired, they become building blocks for children to develop more complex movement patterns and are beneficial for their health [114].

2 studies fell within the *Rudimentary movement* phase. The first aimed to understand the differences between toddlers using a hammer with and without a handle [60]. The second study examined how toddlers (between 1- and 3 years old) manipulate objects according to their age [101]. Both studies aimed at *screening* motor skills.

There were 19 studies involving children who fell under the *Fundamental* movement phase. Out of these, 6 studies [9,66,161,167,190,204] used commercial games which are not explicitly aimed at analysing the performance or correct execution of motor skills by developing children. Another 11 studies [4,41,74,83,90,91,92,94,106,112,160] detected skills not defined as motor development skills. Theore, only 2 studies focused on developmental motor skills: *placing* a virtual coloured ball in its corresponding box [26] and the execution of gross motor skills (*run, gallop, jump forward, slide, hop, skip, kick, catch, strike, throw up/down* and *dribble*) [183].

The remaining 143 studies involved children over 7 years old (*Specialised movement* phase). However, amongst those studies, 48 also involved participants from the *Fundamental* movement phases with 20 studies that used commercial games [5,19,28,38,45,51,53,55,65,77,100,105,115,116,168,170,174,175,184,186], 2 studies provided guidelines for the HCI field [13,164] and 19 used personalised solutions for *Intervention* purposes [3,7,15,16,39,40,43,52,56,70,71,88,110,131,138,145,154,185,194]. From the remaining studies, 6 studies fell in the *Screening* purpose [31,62,73,113,132] and 1 in the *Assessing* locomotor skills [102].

Discussion

To understand the potential of MBT to screen motor skills in developing children, it was essential to understand the type of technology used to detect children's motor skills (RQ1), the motor skills being detected by MBT (RQ2), the purpose for using MBT (RQ3) and which motor development phase MBT was targeting (RQ4).

In terms of the type of technology, excluding the *Others* category, which includes technology designed to recognise one specific skill [1,20,56,82,92,103,110,134,136,203], *Depth sensors* provided the best range detection of motor skills, followed by *pressure mats* as second best and *IMU* as third. C*ameras* were limited to detecting upper limbs' movements which are not part of developmental motor skills. In addition to detecting upper limbs' movements, *IMUs* were also used to recognise locomotor skills such as *stepping* or *running*. *Pressure mats* detected stationary skills such as *standing on one leg*, swaying movement while *standing*, or *lateral steps*. *Depth sensors* provide the broadest detection range encompassing stationary skills: *standing, standing on one leg, imitating posture*; locomotor skills: *stepping, running, jumping*; and fine motor skills: *touching body parts, following a trail, placing an object*. *Marker-based* technology is expensive but provides a very accurate measure of body detection. However, its use was limited to observing kinematics with body joints' range of motion, rotation, and angular velocity.

Mapping all the studies against their purpose and the MBT used (Fig. 3), *depth sensors* also stand out as the only technology implemented across all purpose categories articulated in this review: *screening, assessment, intervention* and *HCI*. For the *Screening* purpose of motor development skills (Table II), depth sensors were used to recognise *jumps forward/high/sideways, hop* and *jog* [22]. Although the dominant technology used for *Screening* purposes was marker-based, it was limited to observing body kinematics to cluster differences between children with and without disability. The remaining technology used for *Screening* purposes to detect motor development skills were the smart toy FutureCube: to *hold a cube* and *build a tower* skill [134]; and a camera to recognise *run, gallop, jump forward, slide, hop, skip, kick, catch, strike, throw up/down* and *dribble* [183]. In terms of *Assessment,* one study combined the *depth sensor* Leap Motion with an eye-tracking camera to support the assessment of the fine motor skills of *placing pegs, threading lace* and *drawing trails* [111], and one study used the *depth sensor* Kinect to classify the execution of the locomotor skills *jumps forward/high/sideways, hop, gallop* and *jog* [102].

To understand whether MBT is suited for a young audience, we

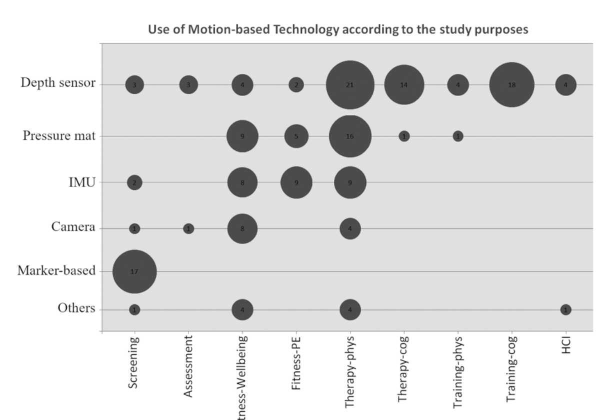

Fig. 3. Distribution of studies according to technologies & application purpose.

analysed the studies considering the MBT used and the participants' age. We selected all the studies where the subjects fell under the *Rudimentary* (1-2 years) and *Fundamental* (2 -7 years) movement phases (Fig. 4). The results show that all motion-based technologies were evaluated with children aged 4 years and older. Since the American Academy of Paediatrics [141] recommends an early detection programme for developmental delays from month 9 (*lexive movement phase*) to years 4-5 (*Fundamental movement phase*), we will focus on the use of MBT for children aged 4 and under.

For the studies where the youngest participants were 4 years old, 7 studies used commercial games [9,16,66,116,138,170,174], 6 studies detected skills not defined as motor development [39,40,41,71,92,106] and 2 studies used *marker-based* technology to observe body kinematics [73,132]. The remaining 2 studies with children aged 4 years old detected the *drawing trail* with the *depth sensor* Leap motion [3] and the *run, gallop, jump forward, slide, hop, skip, kick, catch, strike, throw up/down* and *dribble* motor skills with a *camera* (183).

At age 3, 2 studies used commercial games [28,167], and 3 studies detected skills that are not considered motor development [4,83,145]. The *depth sensor* Microsoft Kinect was used in one study to assess the *jumps forward/high/sideways, hop, gallop* and *jog* locomotor skills [102].

Only 2 studies evaluated MBT with children aged 2 years old. Of these, 1 study used the *depth sensor* Microsoft Kinect to provide guidelines for the HCI community but did not detect motor development skills [164]. The other study used *marker-based* technology to observe the body kinematics of children avoiding obstacles while walking [31].

Finally, at age 1, 2 studies used *marker-based* technology to analyse the arms kinematics of toddlers manipulating objects [60,101].

Overall, depth sensors seem to be the prevailing technology in the range of detection, the field of application and the age range of participants starting at age 2. Thus, depth sensors could be considered the technology with the most potential for detecting and screening motor skills in developing children. However, no single technology detected all the skills defined as developing motor skills. To this end, research on the design of multimodal technologies which combine different types of sensors may offset the shortcomings of a single technology approach. For instance, depth sensors hardly detect bodies while lying on the ground, which hinders the detection of specific developmental skills such as sit-ups or push-ups. On the other hand, low-cost pressure mats would not know about the body posture while detecting pressure. Theore, combining both sensors would facilitate the detection of such skills. Another example would be combining IMU with depth sensors to improve head rotation and manipulative skills such as throwing/catching objects or even fine motor skills such as writing.

Although the literature supports the idea that MBT can be used to recognise developmental motor skills, integrating the complete set of motor skills into a digital screener could be tedious and complex due to the variety of skills. Also, it would require combining different sensors and considering the different ages targeted to adapt the visual instructions to the respective cognitive stages [177]. Professionals use different frameworks for screening, ranging from very extensive [59] to succinct ones [86,188]. The latter proposes a shorter list of 2-4 skills per group (stationary, locomotor, manipulative gross and fine) and could be a good starting point for a digital screener. To this end, a recent study developed a framework that detects and analyses developmental locomotor skills in children aged 4-6 with a depth sensor in real-time [22].

This paper reviews a large number of studies (164) using MBT in order to understand their use and their potential for early detection of motor delay. Although this review is limited to scoping the literature and does not include an assessment or risk of bias of the included articles, it identifies a new research direction with MBT.

Conclusions

This scoping review highlights the lack of technological input, which could increase access to early detection and intervention of developmental delays to support the screening and assessment of motor skills in developing children. In this regard, the use of MBT in the literature was examined to understand its potential and encourage the HCI community to contribute. Many studies (134 out of 164) focused on *Interventions* (*Fitness, Therapy* and *Training)* that used MBT. Most studies (143 out of 164) evaluated children in the *Specialised* development phase when basic motor skills have already been acquired. Out of the 164 studies, only 26 (about 16%) focused on screening or assessing motor skills in developing children (under the age of 7 years). This clearly illustrates that this domain remains underexplored.

Current MBT, particularly depth sensors, has shown great potential in detecting relevant motor skills in the context of motor development. Although several motor skills were being recognised by MBT, the range of skills detected represents only about half of those identified as developmental motor skills (Table II). This suggests that future research should design and implement multimodal approaches combining different MBTs to increase the range and quality of detection. Work investigating the incorporation of technology in the screening and assessment of motor skills development could support professionals and increase access to early detection programmes, assessment, diagnosis, and interventions when/if needed.

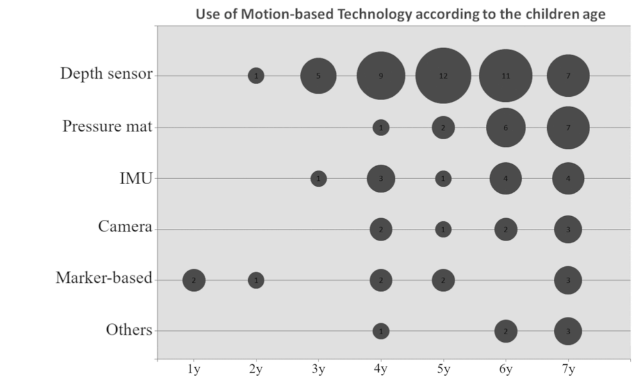

Fig. 4. Distribution of studies according to MBT (vertical axis) & children's age (horizontal axis) of the youngest participant.

CRediT authorship contribution statement

Benoit Bossavit: Conceptualization, Methodology, Data curation, Writing – original draft, Visualization, Investigation, Writing – review & editing. **Inmaculada Arnedillo-Sánchez:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors have no conflicts of interest to disclose.

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Supplementary materials

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