A Mapping Review of Real-Time Movement Sonification Systems for Movement Rehabilitation

Thomas H. Nown, *Graduate Student Member, IEEE*, Priti Upadhyay, Andrew Kerr,
Ivan Andonovic, *Senior Member, IEEE*, Christos Tachtatzis, *Senior Member, IEEE*, and
Madeleine A. Grealy

***Abstract*— Movement sonification is emerging as a useful tool for rehabilitation, with increasing evidence in support of its use. To create such a system requires component considerations outside of typical sonification design choices, such as the dimension of movement to sonify, section of anatomy to track, and methodology of motion capture. This review takes this emerging and highly diverse area of literature and keyword-code existing real-time movement sonification systems, to analyze and highlight current trends in these design choices, as such providing an overview of existing systems. A combination of snowballing through relevant existing reviews and a systematic search of multiple databases were utilized to obtain a list of projects for data extraction. The review categorizes systems into three sections: identifying the link between physical dimension to auditory dimension used in sonification, identifying the target anatomy tracked, identifying the movement tracking system used to monitor the target anatomy. The review proceeds to analyze the systematic mapping of the literature and provide results of the data analysis highlighting common and innovative design choices used, irrespective of application, before discussing the findings in the context of movement rehabilitation. A database containing the mapped keywords assigned to each project are submitted with this review.**

***Index Terms*— Anatomical segments, motion capture, neurorehabilitation, sonification, real-time systems**

I. INTRODUCTION

DISABILITY arising from neurological conditions such as stroke is an increasing concern in present times [1], and without rehabilitation, persisting impairments such as the upper extremity weakness seen in 40% of stroke survivors [2] results in reduced independence and quality of life. Addressing this problem will require low-cost accessible technology that allows individuals to continue rehabilitation alongside established practices. A promising intervention is with the use of real-time movement generated auditory feedback also known as movement sonification [3]. Sonification is the process of translating data to sound, this can occur after the input movement (terminal feedback), or in parallel to the input movement (concurrent feedback), the use of either presents merit, however for this review only the latter is of interest. There are multiple synthesis methods of sonification [4], the most common is through parameter mapping, linking input data to output sound through a predetermined synthesis, and is the preferred methodology for movement sonification in rehabilitation applications. Sonification systems could allow persons undertaking rehabilitation to hear as well as see their movement and this augmented feedback could facilitate motor learning [5]. Interventions using sonification devices are promising, Ghai's 2018 [6] systematic review and meta-analysis of sonification and rhythmic auditory stimulation studies assessing recovering arm functions post-stroke included 23 articles, listing five projects using sonification, showing four different sonification configurations. The review provides evidence for the efficacy of both auditory techniques. Additionally, Guerra *et al.* 2020 [7] published a scoping review on the use of sonification for physical therapy in human movement that contains 35 articles, including 13 randomized control trials (RCT) showing beneficial effects in each. The review also lists 13 different types of motion capture technologies - essential for a movement sonification system - used in the articles. Both existing reviews provide evidence that the use of sonification in a rehabilitation context may improve rehabilitation outcomes. Analyzing the existing reviews from Ghai and Guerra show that the movement sonification systems used are not commercially available off-the-shelf systems, instead they comprise motion capture systems integrated with another smart device (personal computer or otherwise) which contains software components to synthesize audio feedback. The use of these systems for movement sonification is further shown in the systematic review by Wang *et al.* 2017 [8] that investigated the system setups for interactive wearable upper body technologies in a rehabilitation context. However, the review only contained seven articles as having auditory

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T.H.Nown, A.Kerr are with the Department of Biomedical Engineering, University of Strathclyde, Glasgow, UK (e-mail: thomas.nown@strath.ac.uk, a.kerr@strath.ac.uk).

P.Upadhyay, C.Tachtatzis, I.Andonovic are with the Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, UK (email: priti.upadhyay@strath.ac.uk, christos.tachtatzis@strath.ac.uk, i.andonovic@strath.ac.uk).

M.A.Grealy is with the School of Psychological Sciences and Health, University of Strathclyde, Glasgow, UK (email: m.grealy@strath.ac.uk).

feedback. Similarly, due to the set focus and the selection criteria applied in each review paper, results are limited in the number of movement sonification articles identified. As opposed to investigating the holistic impact of the system in respect to rehabilitative applications, in this manuscript the focus is on individual components of movement sonification systems irrespective of application, which will aid in creating a comprehensive review that connects system components together, so that future work may apply them in a rehabilitative context. Three key elements of such systems include the motion capture technology, the anatomy being tracked, and the sonification configurations used. Motion capture technologies used in existing rehabilitation research have been developed and used primarily within a laboratory environment and with a set application, as such many of the systems are inappropriate for alternative environments and applications within rehabilitation for the following reasons: extensive setup, challenging data for sonification (inertial sensors, EMG), limits or constraints movement (ergometer, tablets), high acquisition cost (marker-based motion capture system, goniometer), high environmental dependence (Microsoft Kinect), and/or be unpurchaseable (custom platforms).

The aforementioned reviews which target movement sonification have identified only four options for sonification, which is a low number of approaches when compared to the Dubus and Bresin 2013 [9] review which is a dedicated review on sonification alone. Sonification systems are also used extensively outside of the healthcare domain but their efficacy for rehabilitation has not been assessed. The mapping review presented in this manuscript has been conducted starting from a global overview of current movement sonification systems irrespective of intended application. It intends to: identify trends in system setups, establish if there are motion capture technologies that have been overlooked for rehabilitation applications, provide scope on technological requirements for next generation rehabilitation technologies, and create a resource that future researchers in movement rehabilitation can utilize to develop appropriate and effective rehabilitation tools. To achieve this three key components of movement sonification systems in the literature are identified and analyzed: 1) The types of physical to auditory parameter mapping 2) The part(s) of the body that are tracked 3) The types of tracking technology.

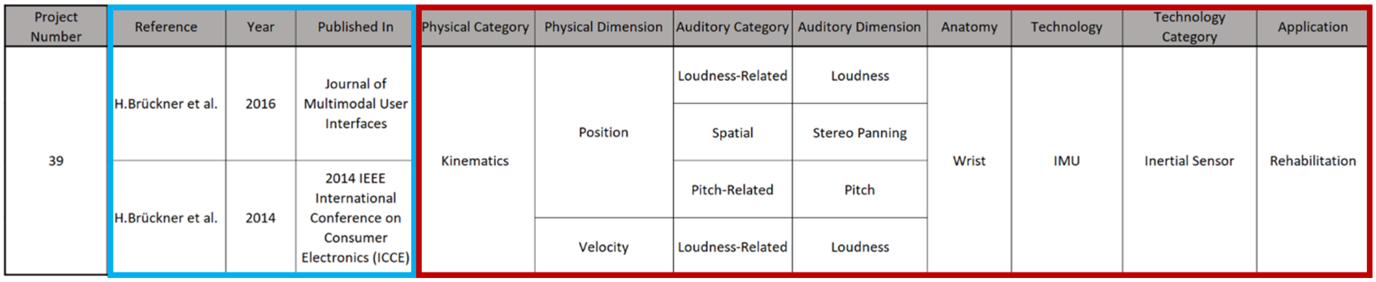
II. METHOD

The review is set as a mapping review or a systematic map, that reports the choice of components used to form a real-time movement sonification system. With further review work expected to achieve meaningful conclusions in the subject area of movement sonification for rehabilitative purposes, this review aims to create a starting point with the formulation and categorization of the existing literature. This review methodology commenced with a systematic search for published articles to identify systems of interest. Components within each system were identified and keyword coded, to form a database of keywords, that were later synthesized into a graphical display. This type of review is not expected to contain a formal appraisal; however, a brief component appraisal will be included based on the criteria outlined in Section V. Following PRISMA guidelines [10], database searches were performed on the 14th of January 2021 on the following electronic literature databases: ACM, IEEE

TABLE I

FULL SEARCH STRATEGIES FOR EACH ELECTRONIC DATABASE.

Electronic Database	**Search Criteria**
ACM	[[Publication Title: sonif*] OR [Abstract: sonif*] OR [Keywords: sonif*]] AND [[All: mov*] OR [All: reach*] OR [All: grasp*] OR [All: point*] OR [All: rotat*] OR [All: acceler*] OR [All: velocit*] OR [All: position] OR [All: danc*] OR [All: kine*]]
IEEE	((((“Publication Title”: Sonification) OR “Author Keywords”: Sonification) OR “Abstract”: Sonification) AND (“All Metadata”: mov* OR “All Metadata”: reaching OR “All Metadata”: grasping OR “All Metadata”: rotat* OR “All Metadata”: acceleration OR “All Metadata”: velocity OR “All Metadata”: position “All Metadata”: danc* OR “All Metadata”: kine*))
PubMed	(sonif*[Title/Abstract]) AND (mov* OR reach* OR grasp* OR point* OR rotat* OR acceler* OR velocit* OR position OR danc* OR kine*) Filters: English
ScienceDirect	“Find articles with these terms”: movement OR reaching OR pointing OR rotating OR acceleration OR velocity OR position OR dancing “Title abstract or author-specified keywords”: sonification
SCOPUS	TITLE-ABS-KEY(sonif*) AND (mov* OR grasp* OR reach* OR point* OR rotat* OR acceler* OR velocity* OR position OR danc* OR kine*) AND (LIMIT-TO(LANGUAGE, “English”)) “Filter by subject area”: Exclude: Biochemistry, Genetics and Molecular Biology; Medicine; Mathematics; Physics and Astronomy; Social Sciences; Agricultural and Biological Sciences; Chemistry; Environmental Science; Materials Science; Chemical Engineering; Earth and Planetary Sciences; Health Professions; Pharmacology, Toxicology and Pharmaceutics; Immunology and Microbiology; Decision Sciences; Energy; Nursing; Veterinary; Business, Management and Accounting; Economics, Econometrics and Finance.
Web of science	#1: (ALL = (mov* OR reach* OR grasp* OR point* OR rotat* OR acceler* OR velocit* OR position OR danc* OR kine*)) #2: (ALL = sonif*) #3: (#1 AND #2) AND LANGUAGE: (English) Filter by Research Area: Exclude: Chemistry; Materials Science; Education Educational Research; Environmental Sciences Ecology; Biochemistry Molecular Biology; Marine Freshwater Biology; Medical Informatics; Behavioral Sciences; Fisheries; Oceanography; Cardiovascular System Cardiology; Pharmacology Pharmacy; Veterinary Sciences; Agriculture; Anesthesiology; Energy Fuels; Geochemistry Geophysics; Life Sciences Biomedicine Other Topics; Mathematical Computational Biology; Remote Sensing; Zoology; Anatomy Morphology; Astronomy Astrophysics; Audiology Speech Language Pathology; Automation Control Systems; Biodiversity Conservation; Communication; Cultural Studies; Dermatology; Food Science Technology; History Philosophy of Science; Mathematics; Mechanics; Meteorology Atmospheric Sciences; Mining Mineral Processing; Polymer Science; Psychiatry; Reproductive Biology; Social Issues; Theater.



Project Number	Reference	Year	Published In	Physical Category	Physical Dimension	Auditory Category	Auditory Dimension	Anatomy	Technology	Technology Category	Application
39	H.Brückner et al.	2016	Journal of Multimodal User Interfaces	Kinematics	Position	Loudness-Related	Loudness	Wrist	IMU	Inertial Sensor	Rehabilitation
						Spatial	Stereo Panning				
	H.Brückner et al.	2014	2014 IEEE International Conference on Consumer Electronics (ICCE)			Pitch-Related	Pitch				
					Velocity	Loudness-Related	Loudness				

Fig. 1. Snippet of database showing completed project data insertion. Each project is allocated a unique identification number, which contains articles identified inside the data columns Reference, Year, Published In, highlighted through light blue. Data from each article was extracted, keyword-coded, and inserted into the remaining data columns, highlighted through dark red.

Xplore, PubMed, ScienceDirect, SCOPUS, Web of Science. Full search strategies for each database are shown in Table I. For each search strategy the word 'sonification' was included to focus the search on relevant projects, and where possible was shortened to sonif* to include variations of the word (such as sonify), the remaining keywords have been selected to cover a wide area of movement-related keywords to increase search results, where similarly each keyword was reduced to include a wildcard symbol allowing for variations of the word to be included.

In addition to articles yielded from the database searches, relevant articles cited in the reference lists of existing literature reviews were also extracted. Duplicate articles were removed, and article abstracts were screened to ensure that the articles met the following inclusion and exclusion criteria. Inclusion criteria applied: 1) Written in English; 2) Describes an implemented system; 3) System monitors human anatomical movement; 4) System produces at least one auditory output; 5) Auditory output described provided real-time feedback, i.e. does not exclusively provide terminal feedback or provide feedback that exceed 100ms from the input [11]. Exclusion criteria applied: 6) System only monitored ocular movements; 7) System where the movement was captured exclusively through a computer mouse, computer keyboard, or touchscreen; 8) System described did not mention a connection between physical movements and an auditory output; 9) System tracks an object, where the object was not attached to a human; 10) System used microphones to record musical instruments as a method to monitor movement; 11) Section of tracked human anatomy was not stated; 12) Movement tracking technology was not stated. The screening of articles for eligibility was carried independently by TN and PU. Initially abstracts were considered for eligibility, before the assessment of the full manuscript. In disagreements between the first two reviewers, a third reviewer (MG) was sought. Following eligibility checks, relevant information was extracted from each article by TN, and assigned a coded keyword into the appropriate category in a data table. Keyword lists are shown in Section III, and an example project entry is shown in Fig. 1.

III. KEYWORD CODING

For data extraction purposes, five keyword lists based on the work of [12] have been created (i) Physical Dimension, (ii) Auditory Category, (iii) Anatomy, (iv) Technology and (v) Application. The classification of every article considered in the review after application of inclusions/exclusion criteria is provided in the Appendix.

A. Physical Dimension

From initial data extraction, nine intermediate-level physical dimension keywords in three high-level categories were selected. The Kinematics category constitutes of Position, Orientation, Joint Angle, Velocity, Acceleration, and Jerkiness. The Kinetics category comprises of Force/Pressure, and Energy. The Other category is set as a catch all category, and keyword, for alternative physical dimensions to the listed above.

B. Auditory Category

For the auditory domain, six high-level category keywords are selected Pitch-Related, Loudness-Related, Temporal, Spatial, Timbral, and Event-Driven. Each category is defined as follows with reference to the sound generated: Event-Driven - Sound sample played upon a movement parameter-based trigger; Loudness-Related - increase or decrease in perceived audio intensity; Pitch-Related - increase or decrease in perceived audio frequency; Spatial - change in perceived location of sound source; Temporal - audio alteration in the time dimension; Timbral - audio alteration in the frequency dimension that excludes changes in pitch or loudness.

C. Anatomy

16 human anatomy keywords taken from [13] were selected to accommodate large and small sections of anatomy required to assign appropriate keywords in this section. The contents of the list are: Head (includes movement of the face and neck) Shoulder, Upper Limb, Upper Arm, Elbow, Forearm, Wrist, Hand (includes movement of fingers) Trunk (includes movement of the chest, abdomen, pelvis and back) Hip, Lower Limb, Thigh, Knee, Lower Leg, Ankle, Foot (includes movement of toes). Additionally, to represent projects that use a physical dimension associated with a tracked center of mass of a person, the keyword Centre of Mass was included. No distinction is made between anterior and posterior sections of each anatomical segment, nor the amount of each segment.

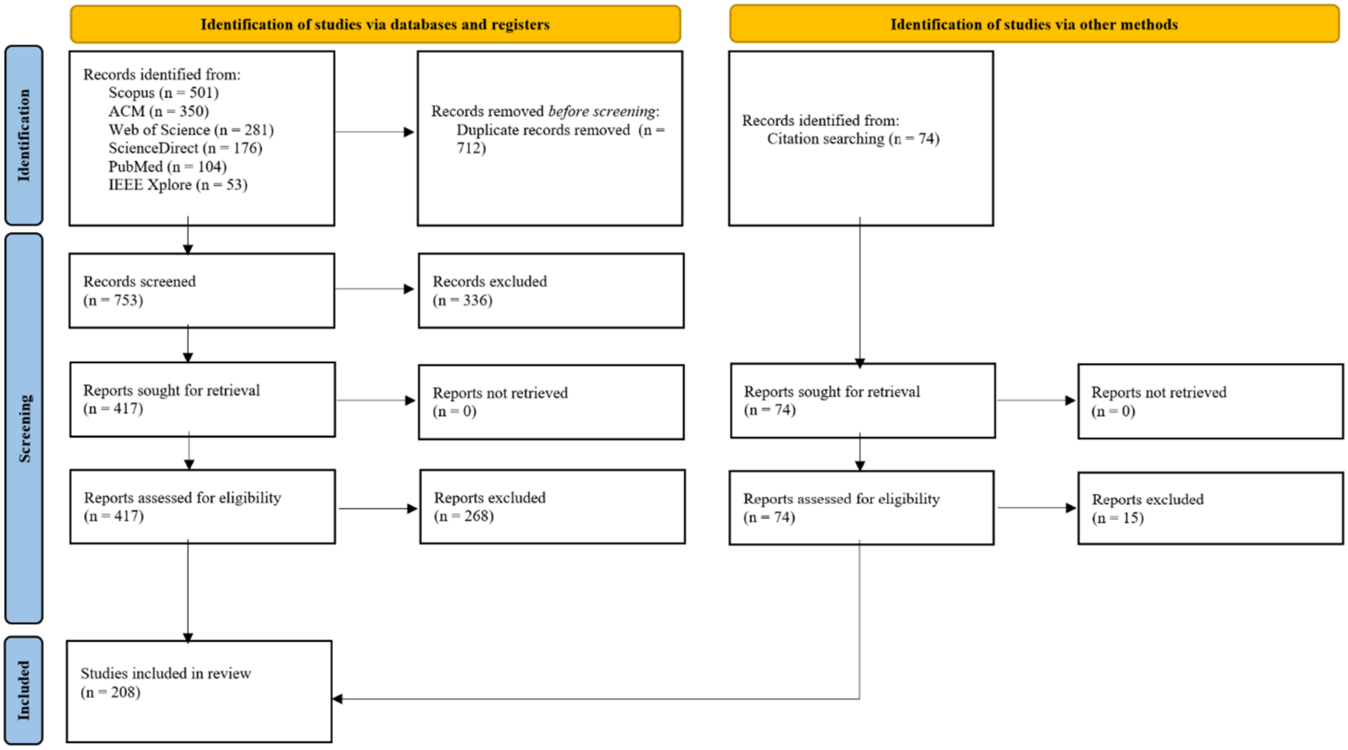


Fig. 2. PRISMA flow diagram, which include searches of databases and other sources. Resulted in 208 articles brought forward for review.

D. Technology

36 technology keywords have been assigned to three high level categories labeled as Inertial Sensor, Camera and Other. The Inertial Sensor category contains: Accelerometer, Gyroscope, IMU, Mobile Phone, and Gaming Controller (IS). The Camera category contains: Marker-Based Motion Capture, Virtual Reality Controller, LEAP Motion Controller, Kinect, Infra-Red, Optical Image, LED-Based Optical Capture, Gaming Controller (Ca). The Other category contains: Graphics Tablet, Microphone, Rotary Encoder, Haptic Device, EMG, MMG, Ergometer, Goniometer, Tendon-Based Parallel Robot, Ultrasonic Sensor, Variable-Resistance Elastic, Bend Sensor, Cadence Sensor, Electromagnetic Tracker, Gaming Balance Board, Tension-Activated Switch, Electrical Contacts, Textile Stretch Sensor, Piezoelectric Transducer Pickup, Infra-Red Proximity Sensor, Footswitch Sensor, Customised Speed Sensor, and Force/Pressure Sensor.

E. Application

Each project included in the review has been assigned a keyword, from a list of 11, to provide context on the type of project that the movement sonification system is used. This list constitutes of: Gait, Sport, Performing Arts, Immersive Environment, Rehabilitation, Body Perception, Balance/Posture, Visual Impairment, Task Performance, Alternative Locomotion, Other.

IV. RESULTS

As shown by Fig. 2 a total of 1465 articles were identified from the search results, with 712 duplicates, resulting in 753 article abstracts screened for eligibility. The full text of 417 articles were assessed for eligibility, resulting in a total of 149 articles for data extraction. From studies identified outside of the database search 74 were identified, with 59 assessed as eligible for inclusion, leading to final total of 208 articles included in this review. For the following results sections, percentages are used as part of the statistical description for the results, however due to the methodology of the review and the complexity of movement sonification systems in the literature, the projects often recorded multiple elements for each category, and consequently for the following data analysis, the sum of the percentages shown in each statement, may exceed 100%. Based on the analysis of the complete data table, graphical visualizations were created to address the following sections.

1) Types of physical to auditory parameter mapping: Keywords entered in the Physical Dimension and Auditory Category data columns have been analyzed separately and in combination for each project. Fig. 3 presents a bubble plot of the chosen movement sonification options with Physical Dimension keywords listed on the vertical axis, and the Auditory Category keywords listed on the horizontal axis. From the 145 projects recorded in the database, 48 distinct types of combinations are recorded, out of a possible 54 - as limited by the keyword categorization - amounting to a total of 397 recorded combinations within the search. No recording was obtained for the combination of Jerkiness to Loudness-Related, Energy to Spatial, Force/Pressure to Spatial, Jerkiness to Spatial, Joint Angle to Spatial, and Other to Spatial. The highest number of recordings for the Physical Dimension is Position with 133,

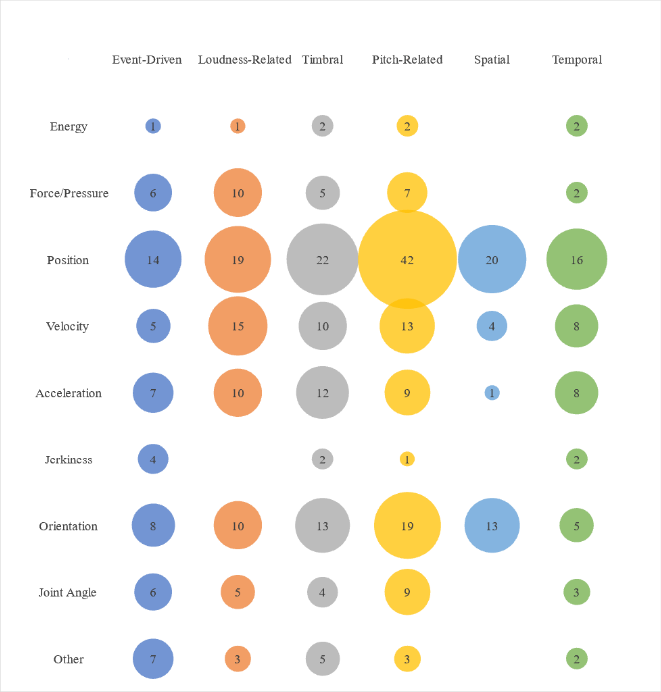


Fig. 3. Bubble plot visualization showing the mapping relationship between Physical Dimension keywords and Auditory Category keywords in all projects. Number displayed shows the number of different projects containing that mapping, with bubble plot size proportional to number shown in the center of each bubble.

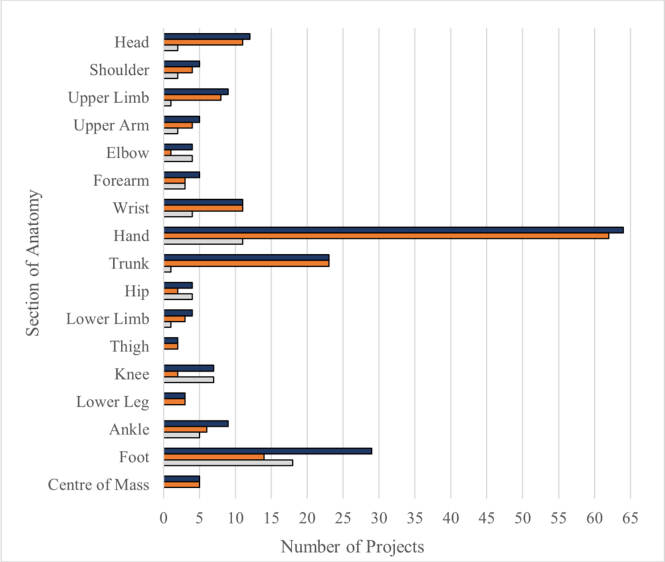


Fig. 4. Bar chart containing allocated 'Anatomy' keywords for each project: i) data visualized in navy blue corresponds to all recorded anatomy keywords, ii) data visualized in orange shows all anatomy entries where at least one of Position, Velocity, Acceleration or Orientation was obtained from that anatomy, iii) data visualized in light gray shows all anatomy entries where a Physical Dimension alternative to Position, Velocity, Acceleration or Orientation was obtained from that anatomy.

amounting to 33.50% of the recorded Physical Dimension keywords, whereas for the Auditory Category, the highest number is Pitch-Related with 105, amounting to 26.45% of the recorded Auditory Category keywords. The combination of Position and Pitch-Related keywords recorded the most with 42 recordings in these results, amounting to 10.58% of all chosen combinations. Other popular keywords in the Physical Dimensions list are Velocity with 55 recordings, Acceleration with 47 recordings and Orientation with 68 recordings in projects. Likewise, other popular keywords in the Auditory Category list are Timbral with 75 recordings and, Loudness-Related with 73 recordings in the reviewed projects. In contrast, the recordings of Energy and Jerkiness in the Physical Dimensions list, have been recorded on less than 10 occasions in these results, whilst for the Auditory Category list, Spatial shown to be the least recorded with 38. Cumulatively Position, Velocity, Acceleration, Orientation (PVAO) amount to 76.32% of the Physical Dimension keywords recorded in the database.

2) The part(s) of the body that are tracked: Keywords entered in the Anatomy list were analyzed independently and in combination with the popularly used Physical Dimension as identified in question 1. Fig. 4 presents three groups of data for this analysis i) all recorded anatomy keywords ii) all recorded anatomy keywords with at least one PVAO Physical Dimension iii) all recorded anatomy keywords with at least one Physical dimension outside of PVAO. Data i) shows all recorded Anatomy keywords consisting of 201 entries from the list of projects. The keyword Hand was recorded the most with 64 entries, which calculates to 44.13% of all projects. Other frequently recorded keywords in this dataset are: Foot with 29 entries calculating to 20.00% of all projects, Trunk with 23 entries calculating to 15.86% of all projects, Head with 12 entries calculating to 8.28% of all projects, and Wrist with 11 entries with 7.59% of all projects. The remaining keywords in this section were each recorded in less than 10 projects. Data ii) shows Anatomy keywords where at least one PVAO Physical Dimension was obtained, amounting to 164 entries from the list of projects. The keyword Hand was recorded the most with 62 entries, which calculates to 42.76% of all projects. Other frequently recorded keywords in this dataset are: Trunk with 23 entries calculating to 15.86% of all projects, Foot with 14 entries calculating to 9.66% of all projects, Head with 11 entries calculating to 7.59% of all projects, and Wrist with 11 entries calculating to 7.59% of all projects. The remaining keywords in this dataset were each recorded in less than 10 projects. Data iii) show Anatomy keywords where at least one Physical Dimension outside of PVAO was obtained from it, amounting to 65 entries from the list of projects. The keyword Foot was recorded the most with 18 entries, which calculates to 12.41% of all projects. Other frequently recorded keywords in this dataset are: Hand with 11 entries calculating to 7.59% of all projects, Knee with seven entries calculating to 4.82% of all projects, Ankle with five entries calculating to 3.45% of all projects. The remaining keywords in this dataset were each recorded in less than five projects.

3) The types of tracking technology: As described in Section III. each technology type was classified to three Technology Categories and the analyzed results are presented in Fig. 5, showing 173 entries overall. The figures in this section have been color coded to represent the technology category assigned. The Inertial Sensor category shown in red contains

TABLE II

TABLE DETAILING THE REMAINING CONTENTS OF THE TRACKING TECHNOLOGY THAT ARE NOT PRESENTED IN FIG. 5. EACH OF THE PRESENTED TECHNOLOGY IN THIS TABLE CONTAIN LESS THAN FIVE RECORDED ENTRIES AND ARE ASSORTED DEPENDING ON THEIR TECHNOLOGY CATEGORY

Remaining Inertial Sensors		**Remaining Other**							
Gyroscope	2	Graphic Tablet	4	MMG	1	Tension-Activated Switch	1
Remaining Camera		Microphone	4	Ultrasonic Sensor	1	Electrical Contacts	1
Virtual Reality Controller	1	Rotary Encoder	2	Variable-Resistance Elastic	1	Textile Stretch Sensor	1
		Haptic Device	2	Bend Sensor	3	Piezoelectric Transducer Pickup	1
Infra-Red	1	Ergometer	3	Cadence Sensor	1	Infra-Red Proximity Sensor	1
Gaming Controller (Ca)	2	Goniometer	4	Electromagnetic Tracker	3	Footswitch	1
		Tendon-Based Parallel Robot	1	Gaming Balance Board	1	Speed Sensor	1

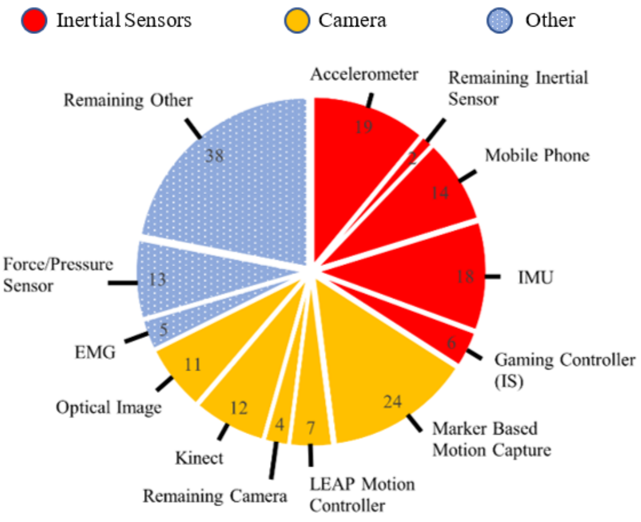


Fig. 5. Pie chart visualization showing all tracking technology keyword recorded in the dataset. Data visualized in red corresponds to Technology keywords categorized in Inertial Sensors. Data visualized in yellow corresponds to Technology keywords categorized in Camera. Data visualized in blue corresponds to Technology keywords categorized in Other. For Fig. 5 all categories with Remaining are detailed in Table II.

59 entries with Accelerometer the most frequently recorded keyword in this category with 19 entries. The Camera category shown in orange contains 58 entries with Marker-Based Motion Capture the most frequently recorded keyword in this category with 23 entries. The Other category shown in blue contains 56 entries with Force/Pressure Sensor keyword the most frequently recorded keyword in this category with 13 entries. All technology entries that are recorded in less than five projects have been grouped depending on their assigned category and represented by a Remaining Inertial Sensor, Remaining Camera, or Remaining Other segment, each keyword grouped in this way is detailed in Table II. Technology categories have also been analyzed in combination with the Anatomy keywords that contained more than 10 entries: Hand, Head, Trunk, Wrist and, Foot (Figures 6(a), 6(b), 6(c), 6(d), 6(e), respectively). These figures have each been color coded in an identical manner as Fig. 5, with the same key. Fig. 6(a) also contains Remaining Inertial Sensor, Remaining Camera and Remaining Other segments to group together technologies that have been recorded once, these segments are expanded in Table III. Fig. 6(a) shows 75 recorded entries, from 23 different technology types split into 17 segments. The Camera category is the most recorded Technology Category with 42 entries calculating to 56.00% of all entries involving the Hand, and the Marker-Based Motion Capture keyword is the most recorded Technology keyword with 15 entries calculating to 20.00% of all entries involving the Hand. Technology keywords associated with Hand also have the highest number of different keywords for each Technology Category recorded. Fig. 6(b), shows 13 recorded entries from seven different technology types used to monitor the Head. The Camera category is the most recorded Technology Category with nine entries calculating to 69.23% of all entries involving the Head, and the Marker-Based Motion Capture keyword is the most recorded Technology keyword with five entries calculating to 38.46% of all entries involving the Head. Fig. 6(c), shows 26 recorded entries from 11 different types of technology used to monitor the Trunk. The Inertial Sensor category is the most recorded Technology Category with 14 entries calculating to 53.85% of all entries involving the Trunk, and the Accelerometer keyword is the most recorded Technology keyword with eight entries calculating to 30.77% of all entries involving the Trunk. Fig. 6(d), shows 12 recorded entries from five different technology types that monitor the Wrist. The Inertial Sensor category is the most recorded Technology Category with 10 entries calculating to 83.33% of all entries involving the Wrist, and the IMU keyword is the most recorded Technology keyword with six entries calculating to 50.00% of all entries involving the Wrist. Fig. 6(e), shows a total of 51 entries from 13 different types of technology that are used to monitor the Foot. The Other category is the most recorded Technology Category with 22 entries calculating to 43.14% of all entries involving the Foot, and the Force/Pressure Sensor keyword is the most recorded Technology keyword with 10 entries calculating to 19.60% of all entries involving the Foot.

V. DISCUSSION

Based on data available in 2020 the annual societal cost of stroke is estimated to be £26 billion for the UK, with

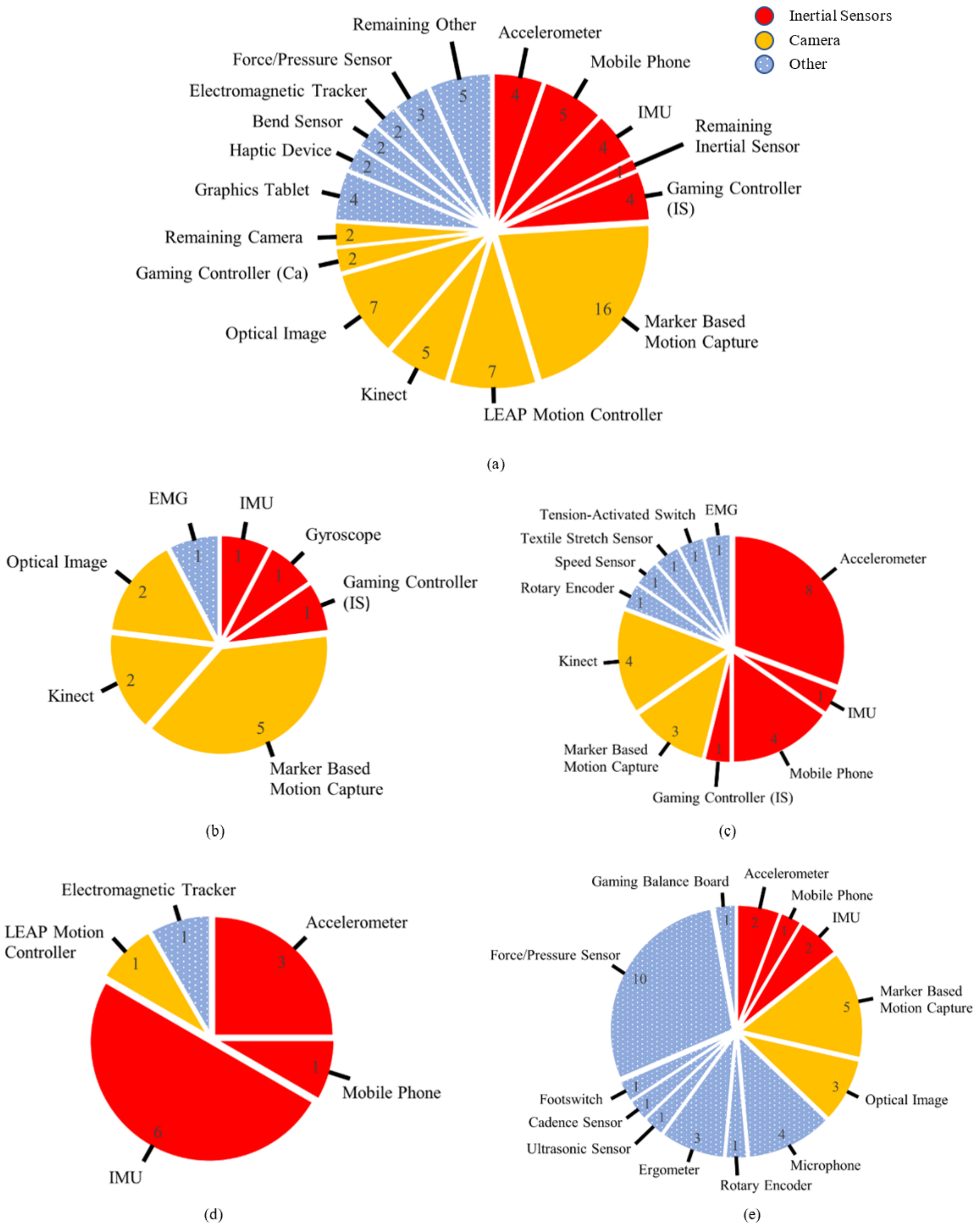


Fig. 6. Pie chart visualization showing the tracking technology keywords recorded in the database, filtered to show popularly used tracked anatomy as follows: (a) Hand, (b) Head, (c) Trunk, (d) Wrist, (e) Foot. Data visualized in red corresponds to Technology keywords categorized in Inertial Sensors. Data visualized in yellow corresponds to Technology keywords categorized in Camera. Data visualized in blue corresponds to Technology keywords categorized in Other. For (a), all categories with 'Remaining' are detailed in Table III.

TABLE III
TABLE DETAILING THE REMAINING CONTENTS OF THE TRACKING TECHNOLOGY THAT ARE NOT PRESENTED IN FIG. 6(A). EACH OF THE PRESENTED TECHNOLOGY IN THIS TABLE CONTAIN ONE RECORDED ENTRY AND ARE ASSORTED DEPENDING ON THEIR TECHNOLOGY CATEGORY

Remaining Inertial Sensors	
Gyroscope	1
Remaining Camera	
Infra-Red	1
Virtual Reality Controller	1
Remaining Other	
Tendon-Based Parallel Robot	1
Electrical Contacts	1
Piezoelectric Transducer Pickup	1
Infra-Red Proximity Sensor	1
Rotary Encoder	1

informal care costs attributed to the most [14], with prediction of rising costs in future years. Inevitably, improved rehabilitation outcomes and improved management of resulting health conditions would allow stroke survivors to regain some level of independence and therefore reduce care costs. As such in addition to the desire for more effective rehabilitation interventions, a method that reduces societal costs are sought after. Movement rehabilitation is progressing from hospital-centered frameworks to home-based frameworks [15], and as such next-generation rehabilitation technologies need to accommodate this adaption. Additionally, there are greater calls for rehabilitation interventions to be based on a person-centered approach [16] i.e. meeting the needs and requirement of the person at every stage of the process. As impairment can range from mild to severe [17], and the desire for rehabilitative techniques to mimic daily-life activities [18], rehabilitation will therefore ideally require a system that is cost-effective, accessible to use, flexible to accommodate variation in capacity and activation, and versatile to accommodate different rehabilitation exercises. The results of this review highlight the diversity of components chosen for a real-time movement sonification system in the literature. Each project was keyword-coded based on the system(s) detailed in the composing article(s), and the resulting keyword database was synthesized to produce visual displays in support of addressing the research topics stated in this review. Disaggregation of each movement sonification system to the three principal components (motion tracking technology, anatomy and sonification) allows the identification of the components that are most popular in the literature. The present discussion looks to view the identified system components in terms of motion tracking and sonification configuration and provide perspective on appropriateness to movement rehabilitation.

A. Motion Capture Technology

Existing rehabilitation projects identified in this review have made use of a variety of technologies to monitor PVAO of a tracked segment of anatomy. For each technology type, a perspective on the acquisition costs is included where possible, with approximate price of <\$100 labeled as 'low cost', \$100 - \$500 labeled as 'moderate cost', and >\$500 labeled as 'high cost'. Technologies that have an undisclosed acquisition cost, have no label assigned. Due to the categorization of technologies in this manuscript, there are ranges of costs for most of these technology categories, as dependent on the requirements and capabilities of the products in the category, as such these labels are intended as guides when considering costs of each technology. Similarly, accuracy is an important characteristic to consider when selecting a motion capture system as an input to a real-time movement sonification system, and varies depending on multiple aspects including: technology type, number of units, intended application, choice of kinematics and, capture frequency. Due to this variability, generalizing the accuracy of each technology would be inappropriate and is absent from this discussion. Further research into accuracy requirements and competency is strongly recommended before selecting a technology, with information available in existing reviews, such as [19]. Finally, although the use of a computer mouse, computer keyboard and, touchscreen technologies have commonly been used as input interfaces for commercialized devices and as such are accessible low-cost motion tracking technologies, the use of these devices come with limited tracking volume, and are not considered applicable to functional training, as such these technologies are excluded from this manuscript. Inertial sensors embedded in mobile phones used in [20] were attached to the wrist and ankle of users to monitor clinical routines, and in [21] to track wrist flexion-extension and radial-ulnar movements. Multiple IMUs were utilized by [22]–[27] to monitor an upper-limb whilst performing task-oriented movements, whereas a single IMU was used in [28] to monitor reaching movements. The use of inertial sensor technologies, such as the IMU and the sensors integrated in a mobile device, allows for a technology that is versatile in tracking gross movement for a low cost, however, for the application of a movement sonification system the data can require extensive filtering and manipulation to obtain the desired physical dimension. Repurposed gaming controllers are used widely motion capture devices for entertainment-alternative applications, with the acquisition of these technologies available at a low cost being a key reason. Examples include the Wiimote as applied in a rehabilitative context by [29] to detect shoulder abduction/adduction and compensatory trunk movements; used outside of a rehabilitative context by [30], and [31]. Other examples can be seen through the Wii Balance Board as demonstrated by [32]; the PlayStation Move motion controllers as demonstrated by [33]; the Microsoft Kinect as demonstrated by [34]. However, with exception to the PlayStation Move Controllers, all the gaming controllers listed above have been discontinued. The Microsoft Kinect for Xbox on the other hand has a successor named Microsoft Azure Kinect SDK which is available for purchase, and could be used in future motion tracking applications, however as noted in [35], there are limitations with using this technology, including object reflectivity issues, and degraded performance in outdoor environments. In terms of a motion tracking solution, the minimum requirement to use the Azure Kinect body tracking on a Windows PC are as follows: Seventh Gen Inten CoreTM i5 Processor (Quad Core 2.4GHz or faster), 4 GB Memory, NVIDIA GEFORCE GTX 1050 or equivalent, Dedicated USB3 port. A host device with these requirements along with the device itself, leads to a high cost for this technology as a rehabilitation commodity to be sold to the public. Alternative projects that make use of multiple motion capture technologies include [36] who used an accelerometer for a synchronous task and a Microsoft Kinect to track sitting posture; [37]–[40] developed a framework referred as Go-with-the-flow which used embedded inertial sensors in a mobile phone, or the Microsoft Kinect, to monitor the trunk and upper limb. Marker-based motion capture systems, is the term selected in this manuscript to represent optical motion capture systems that track retroreflective markers attached to target locations. Although this type of technology is considered the gold-standard of motion capture [41] the system comes at a high cost, and requires dedicated space, calibration time and trained personnel to maximize the capabilities of this technology. Examples of use in a rehabilitative context can be seen through: [42] [43], to capture reaching and grasping movements; [44] to capture the upper-body during rehabilitation exercises; [45] to capture hand movements during a figure tracing task. A LEAP motion controller was utilized by [46], and included in a system termed SonicHand by [47], to track hand and wrist movements. This low cost technology is designed to track the hand of a user, within the field of view (FOV) of the camera. However as noted by [48], the limited FOV, dependency on environmental conditions, and performance with objects in FOV, are limitations with using this technology for home-based rehabilitative applications. Motion capture systems that make use of an electromagnetic field and attachable sensors (that act as markers) have been labeled as an electromagnetic tracker in this manuscript, as shown in [49] and [50] to monitor reaching movements, such systems are able to monitor the position and orientation of each sensor. However, the resolution of the system is distance dependent from the field source, which restricts the appropriate range of operation for motion capture. Haptic devices, such as the SensAble PHANToM Desktop haptic device, a computer periphery device that operates by the user moving a stylus attached to a robotic arm, have also been used as a motion capture device. Usually applications with haptic devices will only focus on their haptic feedback capabilities, however [51], and [52], incorporated additional audio feedback using the motion capture capabilities of the device, to create a multimodal system for their projects. A graphics tablet, although conventionally used for drawing applications, was used as a motion capture system as part of a writing rehabilitation task [53], as such capturing the movements of the hand on a 2D-plane, albeit in a limited range of space. The technology is available at low cost, but has a large range of cost as dependent on size of working area, resolution, and quality of product. Other motion capture technologies have been created as wearable systems for rehabilitative applications, including a garment integrated with stretch sensors was created by [54] to monitor the upper body during rehabilitative exercises; a bespoke glove with integrated electrical contacts was created in [55], [56] to detect connection between the thumb and specific hand locations in a rhythmical serious game. Both systems show the potential and limitations of wearable systems, with the garment allowing motion capture of the entire upper body with a single item but creating difficulty for a hemiparetic user (who would struggle to clothe) in using the item. In contrast the bespoke glove would be easier to clothe and use, however the motion capture would be restricted to hand movements and postures. Outside of rehabilitation, existing projects have made use of alternative off-the-shelf technologies to capture human movement for their systems. Virtual reality (VR) systems and the handheld controllers associated with them are one example. Reference [57] shows an example of a virtual reality sonification system, tested with the Samsung HMD Odyssey Windows Mixed Reality Headset. The VR market is an emerging competitive market, as companies look to provide entertainment experiences through these systems, as such off-the-shelf systems vary in price from moderate to high cost, depending on the desired capabilities and specification of the system. VR either with associated controllers or in combination with a LEAP motion controller could provide an effective environment for real-time audiovisual feedback, and as technology in this area is advancing in quality, with a healthy competitive market, leads to a promising motion capture system for upper-limb rehabilitation. The use of RGB camera-based devices, labeled in this manuscript as Optical Image, is an established means of capturing images, however the use of these images as a means of motion tracking is of interest in this review. As observed from the projects identified in search list, there are two methods of using this technology, one is using a mobile camera to track an anatomy (typically the hand holding the camera) in relation to an observable fixed reference (example shown in [58] , and the other method is with a fixed camera tracking a mobile section of anatomy (example shown in [59]. The use of this system is observed in many applications including visual impairment [58], [60], sport [59], [61], performing arts [62], [63], gait rehabilitation [64], immersive environment [65], task performance [66], or for other purposes [67], [68]. Likewise smart phones typically contain an RGB camera as standard, providing an accessible means of capturing movement, available at low cost. However, the performance of this technology is dependent on the environment. As the technology market is a competitive market with a range of specifications for desired capabilities and costs, the development and use of these systems show promise for rehabilitative applications. An ergometer, such as an exercise bike or an indoor rower, although limits the actions of a user to specific activity-dependent movement, are popularly used as exercise equipment. Although other projects make use of an ergometer in their project, only [69]–[71] have used the technology for motion capture system in their real-time movement sonification system. The technology is widely available for purchase, however, the systems are unportable and range from moderate to high cost for acquisition. Rotary encoder(s), used to determine the angular position of a rotational shaft, were applied to a cycling task [72] and a rowing task [73]. Within the projects identified in this review, these encoders are low to moderate cost attachments to existing ergometers, however other projects outside of the remit of this review have made use of encoders as part of robot-assisted lower extremity exoskeleton [74], as such there is vindication of using this technology as a means of capturing movement, but this requires additional integrated components for a usable system. Goniometers are instruments that when applied to human biomechanics context, are used to measure joint angles. In their primitive analogue form, goniometers are low cost and accessible instruments, but are inadequate for real-time monitoring. Reference [75] demonstrated a setup utilizing potentiometers as goniometers to create a real-time system, this type of technology is otherwise known as an electrogoniometer, which are commercially available, however this option comes at a high cost. Examples of use can be seen through [76] and [77]. The use of a microphone, as a method of obtaining sound from the foot-ground interaction, has been used in many projects as a means of an input stream for a movement sonification system, with most recent examples including [78]–[81], all for walking purposes, and [82] as part of a trampoline sonification system. The use of this technology for motion capture, although innovative in providing motion capture of the foot-ground interaction, would only be applicable for highly specific applications. Although this technology is available at low cost, the use of microphones attributing to moderate to high costs have generally been used. Force/Pressure sensors are commonly used as motion capture devices in the literature, although none have been recorded for use in an upper-body rehabilitative context, examples of use can be found with performing arts [83] [84], to affect body perception [85]–[87], monitor cycling [70], [71], monitor skiing [88], gait rehabilitative purposes [89]–[92], sports application [93]–[95], or with use as an interface [96]. As the sensor requires compression to result in an electrical resistance change, human motion capture therefore is limited to interaction with a surface, however due to the low cost, and high environmental versatility of the sensor, this remains a popular sensor type for motion capture. As shown in Section IV, the use of force or pressure sensors is especially popular in combination with motion tracking of the foot, or feet, of a person. Ultrasonic sensors utilize ultrasonic waves as a method of measuring distance an example of use can be seen with [97] to detect foot elevation from the floor whilst walking. Similarly with force/pressure sensors, this technology is considered low cost and versatile, however the application limitations differ as ultrasonic sensors require distance from a perpendicular surface to be utilized effectively. Bend sensors, otherwise known as flex sensors, are variable resistors with flex-dependent resistance. Projects that use such sensors have applied them to detect postures of the hand [98], [99], and to detect joint angle around the elbow [100]. Although the sensors are low cost, and versatile, multiple flex sensors are required per joint to capture movement in multiple axes. Electromyography and Magnetomyography (EMG and MMG respectively) are instruments used to detect muscle activation by monitoring the neural signals sent to that muscle. Researchers that use such technologies for motion capture generally use surface electromyography (sEMG) allowing for safer monitoring of muscle activation, these generally have high cost. As many sensors are required to monitor many synergistic or antagonistic muscle groups, and extensive signal processing is required for each sensor, this limits the appropriateness of using such a technology type for complex movements. However, examples of use can be seen with [101] in a facial expression sonification project and with [102]. Other technologies have been applied to the projects identified, these are generally considered to be very specific to the application of the movement sonification system. A tendon-based parallel robot was developed and used in a rowing task [103]. A cadence sensor was used in a cycling motivational investigation [104]. Multiple infra-red proximity sensors were used to capture hand movements in a specific 3D volume [105]. A piezoelectric transducer pickup was used in a sonic interactive surface [106]. There are also recorded projects that made use of switches [107], [108], variable-resistance elastic [109], or a speed sensor [110], [111]. From the existing motion capture systems identified in the literature, several potential technologies could be utilized for motion capture purposes in a home-based stroke rehabilitative context. Inertial sensors are widely accessible with low cost and if raw acceleration or angular velocity are appropriately utilized, these devices provide an excellent candidate technology. However, metrics such as gravity removed linear acceleration and orientation require additional data fusion between the measurands. If these are to be further processed to obtain velocity or position, integration and drift errors accumulate requiring additional calibration, anchoring or use of additional devices that increase the cost and difficulties with setup. The use of camera technologies such as Azure Kinect or LEAP motion has potential, especially with the capability of measuring position leading to greater flexibility in desired physical dimension, however the cons of high cost and environmental dependence could demotivate users. Whereas other technologies have various pros and cons that generally make them a good option depending on the intended application, but not for others. There also remains a possibility to combine the capabilities of multiple motion capture devices to obtain a synergistically superior system. One such example could be through combining portable sensors to an ergometer, allowing for multimodal bilateral training, that is not only available for home use, but could be taken to a gym, or physiotherapy session. Overall, the diversity in motion capture technology chosen in the literature is justified as an ideal motion capture system is still absent.

B. Sonification Mapping

As mentioned in Section I. existing reviews from Ghai and Guerra have overall come to positive conclusions with regards to utilizing auditory techniques for rehabilitative purposes, however there is minimal spotlight on the sonification configurations utilized in the reviewed articles. Although some studies have been conducted evaluating sonification mapping choices [112], [113] evidence-based guidelines for real-time movement sonification mapping are currently absent. As such creating an effective movement sonification system is likely to require a more trial-and-error iterative approach, as opposed to an efficient systematic approach. The results of this manuscript provides information on the available (or lack of) choices in the existing literature and motivate future system creators to select, test, and compare their system with those identified in the literature, and therefore future work can provide evidence on the efficacy of these sound configurations for upper-limb stroke rehabilitation. From the existing rehabilitation projects, a wide range of sonification options have been utilized. The following projects contain position, the most chosen physical dimension, in simple sonification designs. References [49] and [54] linked position to pitch. Reference [50] linked position to loudness and orientation to stereo panning. Reference [29] linked position to an audio sample, and orientation to loudness and to trigger an audio sample. Reference [20] linked position and velocity to trigger an audio sample. Reference [45] linked position to the addition of noise. References [55] and [56] linked position to melody, and loudness. Reference [114] linked position to timbre and loudness, and acceleration to polyphonic content. References [22], [23] linked position to loudness, pitch, and stereo panning, and linked velocity to loudness. References [24] [25], [115] linked position to pitch, stereo panning, and brightness, and linked velocity to loudness. References [28] linked position to pitch, tempo, and melody. References [46], [27] [116] linked position to pitch, brightness, instrumentation, and loudness. Sonification designs that do not use position appear in this area as well, [52] linked velocity to pitch, [53] linked velocity to melody, and force generated is linked to loudness. Reference [21] linked velocity to loudness and tempo, and linked orientation to pitch and timbre. Other rehabilitation projects include a range of sonification options that are implemented in their system, [37]–[39], and [40] contains 14 different mappings, [47] contains six different mappings, [44] contains five different mappings, [42] and [43] contains seven different mappings. Details for each project are listed in the database attached in the appendix. The use of position as a physical dimension mapping option, and a pitch-related auditory mapping option are predominantly chosen in the literature, either in combination or with other types of mappings. Velocity as part of a sonification mapping is also favored, especially in combination with the following auditory categories: loudness as demonstrated through [6], [117], [118] and [75]; timbral as demonstrated through [119]–[123]; pitch as demonstrated by [124]–[126]. Likewise, orientation is a preferred physical dimension, and is used most in combination with the following auditory categories: timbral as demonstrated by [127], [33], [128]; pitch as demonstrated by [85], [30], [129], [130]; spatial as demonstrated by [131]–[133]. Finally, acceleration is generally chosen in combination with the following auditory categories: loudness as demonstrated by [134], [135]; timbral as demonstrated by [136]–[141]; pitch as demonstrated by [142]–[144]. Outside of the PVAO physical dimensions, data obtained as force or pressure, as dictated by the use of a force or pressure sensor, has been combined with sampled sounds [145], and changes in loudness [84], timbral [32], pitch [69] and, temporal-related [71] auditory feedback. There are also projects that make use of multiple mappings that include force or pressure as a physical dimension, examples include [83], [89]–[91], [94], [95]. The angle difference calculated around a joint has been used as input physical dimension for movement sonification purposes, examples of use can be seen in combination with sampled sounds [146], and changes in loudness [76], timbral [126], pitch [147] and, temporal-related [148] auditory changes. Alternative physical dimensions used as the input dimension to sonification mappings have relatively low numbers in comparison to the aforementioned sections. Jerkiness, is calculated and used within six projects [149]–[159]. Energy is calculated and used within three projects, [154]–[156], [160]–[162]. Categorized in the Other keyword category are alternative physical dimensions that are highly specific to the application that the system is developed for. These include contact with a surface [78], [79], [163], electromyography signals [101], [164], magnetomyography signals [102], and facial expressions [63]. The use of a physical dimension and auditory dimension seems to play a part in the effectiveness of a movement sonification intervention, however as of writing, insufficient evidence is available on which combinations provide the most effective results for motor learning, or movement rehabilitation. Based on the results of this review, established combinations of physical dimensions to auditory dimensions can be identified and brought forward for direct comparison studies for rehabilitative purposes.

VI. CONCLUSION

The mapping review presented provides an overview of real-time movement sonification systems, by identifying three main components for system design: the sonification design choice, the anatomy monitored, and the motion capture technology used. From 208 articles identified, 145 projects were keyword-coded, analyzed, and proceeding results visually synthesized, to present a representation of the systems used in the existing literature. Results from the analysis highlight the diversity of components used in the literature, with 48 different high-level combinations of sonification mapping, 36 technology types, and 17 sections of anatomy, identified. The highest recorded components in each section consisted of: the position of the target anatomy is parameter mapped to the pitch of the auditory feedback; a marker-based motion capture system is used as a motion tracking technology; a hand of an actor as an input to the system. Additionally, the review describes technologies that could be used for rehabilitative purposes, whilst highlighting the limitations of their use. The review also describes the sonification mapping used, detailing the popular combinations used for each physical dimension. The outcomes of this review will be useful for future movement sonification system designers in creating a system for their intended application, by providing a resource that allows easy access to relevant literature dependent on their application and requirements. From a rehabilitative perspective, future work should look towards identifying sonification comparison studies, and to continue developing motion capture technologies to provide an accessible, low-cost, versatile device for users as part of a real-time movement sonification system.

APPENDIX

Insert Excel Spreadsheet here.

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Thomas H. Nown (GS'20) received an M.Eng. degree in electrical and electronic Engineering from the Faculty of Engineering, University of Nottingham, UK, in 2016. He is currently working towards an Eng.D. degree in biomedical engineering at the University of Strathclyde, Glasgow, UK, on the subject of movement sonification system development for upper-limb rehabilitation of stroke survivors. Mr. Nown is an Associate Member of the Institute of Physics and Engineering in Medicine.