Original Article

CLINICAL REHABILITATION

Clinical Rehabilitation
1–17

DOI: 10.1177/02692155221141039
journals.sagepub.com/home/cre
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Wearable technologies for monitoring aquatic exercises: A systematic review

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Abstract

Objective: To review methods for aquatic exercise monitoring using wearables.
Data sources: Database search of PubMed, IEEEXplore, Scopus and Web of Science based on keywords, considering articles from the year 2000. The last search was performed on 26 October 2022.
Review methods: Following the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) protocol, eligible articles on water exercises were selected and summarized. Further screening process concentrated on studies exploiting wearable devices, organized according to demographics, purpose, protocols, outcomes and methods. A custom critical appraisal questionnaire was applied.
Results: Out of the 1062 articles identified, 572 were considered eligible and subjected to preliminary synthesis. The final review focused on 27 articles featuring wearable devices applied to aquatic exercises. Four studies were disregarded as they applied wearable devices to determine daily physical activity or for sleep monitoring after training. Summary tables of 23 studies exploiting wearable devices for underwater motion analysis are provided, specifying the investigated parameters, major outcomes and study quality. This review identified four research gaps: (a) the absence of clinical protocols for underwater motion studies, (b) a deficit of whole-body studies, (c) the lack of longitudinal studies monitored via wearable devices and (d) the reliance of underwater studies on measurement and assessment methods developed for land-based investigations.
Conclusions: This review emphasizes the need for both technological and methodological improvements for underwater motion analysis studies using wearables. We advocate for longitudinal clinical investigations with wearables to substantiate water exercise as an addition or replacement for land-based physical activity.

Keywords

Aquatic exercises, water, hydrotherapy, wearables, IMU, systematic review

Received February 17, 2022; accepted November 8, 2022

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Introduction

Aquatic exercises and hydrotherapy are especially well suited where traditional land-based physical therapies are known to be potentially harmful,[1] due to the weight-reducing and stabilizing forces of buoyancy and drag that water provides.[2] Systematic reviews of aquatic motion analysis have focused on specific dysfunctions or conditions, such as neurological diseases,[1,2] fibromyalgia,[3] asthma,[4] spinal cord injury,[5,6] haemophilia[7] and stroke[8–10.] Additional reviews have also investigated the physiological effects of water,[11] evaluated the use of aquatic exercise for healthy subjects[12,13] and for glycaemia[14] and studied the biophysical differences between aquatic and land-based treatments.[15] The presence of water generally constrains the application of classical investigative tools for motion analysis, including motion capture and electromyography.[16,17] Currently, systematic investigations of underwater motion remain scarce: two reviews explored the literature on surface electromyography for exercises and gait in water, and for deep water running,[18,19] while Heywood et al.[20] focused on spatiotemporal and kinematic parameters in water. Lastly, Marinho et al.[21] surveyed the use of wearable Inertial Measurement Units (IMUs) for underwater human monitoring for non-swimming activities.

The objective of this review is to identify major research gaps and determine potential improvements for future clinical studies by addressing two research questions. First, what are the most frequently applied methods for aquatic motion analysis over the past two decades? Second, what major gaps remain when considering the existing body of literature using IMU wearable devices for monitoring of underwater exercises, and what can be done to improve the understanding of aquatic motion analysis?

The current review provides a systematic assessment of the state of the art of aquatic exercises and hydrotherapy studies, following the Preferred Reporting Items for Systematic Review and Meta-Analyses[22] (PRISMA) method.

Methods

The review protocol was registered in the international database PROSPERO (CRD42022316782). The selected literature repositories were searched using specific keywords and considering only peer-reviewed articles published from 2000 onward. The final search was performed on 26 October 2022 by two independent reviewers.

The identification of candidate English-language literature was performed on *PubMed*, *IEEE Xplore*, *Web of Science* and *Scopus* databases. The complete list of keywords and filters applied is reported in Appendix (Table A1), as well as the number of articles selected per database. Due to the large number of potentially significant studies, the terms underwater, water and aquatic were used to refine the field of interest. The keyword combinations used for screening concerned general exercise terms including rehabilitation, training, hydrotherapy and kinematic. In addition, the exercise-specific keywords treadmill, gait and walk were included to improve the specificity of the filtering stage of the review. The keywords IMU, electromyography, motion capture, force plate and wearable devices were also included as they represent the most current aquatic exercise monitoring methods.

Potentially relevant articles and additional articles identified through citation searching were screened following PRISMA after removing duplicates (Figure 1). To reduce errors and avoid risk of bias, the identified articles were filtered, sorted, examined and evaluated by two independent authors. Based on the title and abstract, articles outside the scope of the research questions, review articles, publications featuring animals or robots, book chapters and theses, discussion articles and editorials unrelated to aquatic exercises were excluded. Subsequently, further works were omitted which were unrelated to active hydrotherapy including shower massages, spa therapies or passive water immersion, swimming, diving or other recreational water sports. In addition, articles developing mathematical models, works which provided guidelines for clinical study designs, physical activities surveys or publications testing novel waterproofing methodologies and tools were also excluded. A preliminary synthesis was conducted on the remaining eligible articles. The synthesis was used to define the state of the art, organize the studies by publication year, demographics, general characteristics and the methods used to investigate motion.

Finally, PRISMA stage was considered solely the eligible articles exploiting wearable devices. A qualitative synthesis of works using wearable technologies for underwater motion analysis was conducted because a meta-analysis was considered inappropriate due to the substantial heterogeneity of the remaining studies. Articles using wearable devices to quantify daily physical activity or for sleep monitoring were disregarded from the qualitative synthesis.

An overview of the demographics and characteristics of the investigation, choice of protocol, evaluation method and estimated outcomes was generated. A custom critical appraisal questionnaire of the studies was created based on STROBE,[23] CASP[24] and McMaster[25] assessment tools. The custom questionnaire consists of nineteen questions and is provided in Table A2. Articles were evaluated according to positive, negative, partial answer or not applicability of the inquiry.

Results

Preliminary synthesis of the eligible articles

After removing duplicates, a total of 1062 potentially relevant articles were identified and filtered producing 572 eligible articles (Figure 1). In the period ranging from 2000 to 2010, 142 (25%) articles were published on water exercise and from the years 2011 to 2022, 430 (75%) articles were identified, indicating a growing interest of researchers and clinicians in aquatic activities.

Examining the structure of the eligible studies, 333 (58%) works analysed the whole rehabilitation cycle over multiple weeks to evaluate the effect of the long-term protocols through pre/post comparison. The remaining 239 (42%) studies investigated the subjects once, and generally presented results based on 5–10 repetitions of the investigated task to estimate the differences between water and land-based exercises.

Slightly more than half of the eligible articles (293, 51%) involved healthy subjects. The remaining 279 focused on patients with disorders and chronic conditions, 20 of which included a healthy control group. The most common conditions investigated were neurological impairments (100) including Parkinson's disease, stroke, multiple sclerosis, incomplete spinal cord injury and intellectual disabilities. The second most common conditions pain-related disorders including arthritis, osteoporosis, fibromyalgia and non-specific back pain (75). A total of 39 studies considered cardiovascular or respiratory diseases. Twenty articles involved children and 16 considered orthopaedic conditions. The remaining 29 works focused the investigation on various pathologies and conditions as diabetes, obesity and pregnancy.

The outcomes of water activities were monitored in 318 of the 572 eligible studies with quantitative methods. Among them, 88 works exploited two or more of these tools. The most common methodology exploited was the dynamometer (94), which was applied to estimate strength and muscular endurance. Force plates and pressure sensors were used in 88 studies to investigate the dynamic component of motion as ground reaction forces or to evaluate balance ability and proprioception. Kinematics were investigated with motion capture in 84 articles using optoelectronic[26] systems based on infrared cameras or video analysis using standard commercial cameras and smartphones. Electromyography was used in 81 articles to record the electric signals generated by muscle contraction via surface or intramuscular electrodes. A total of 34 studies exploited goniometers to measure joints' range of motion, 27 articles used IMU devices to investigate motion using small, lightweight data loggers outfitted with a combination of triaxial accelerometer, gyroscope and magnetometer sensors. The remaining set of 13 studies made use of other highly customised technologies. The most common combinations of monitoring systems were motion capture and electromyography (17) or force plates (10) or both (6). Wearables were used in combination with motion capture, force plates and electromyography in 12 studies.

The other main category of techniques employed to monitor aquatic exercises are methods for metabolic assessments. The most common methods were heart rate and respiratory gas analysis. Semi-quantitative and qualitative methods for motion analysis included tests, scales and questionnaires, and were focused towards determining patient conditions, mobility and the overall effectiveness of water-based therapies. Furthermore, these methods can be categorized into seven distinct groups: (a) functional tests of motion-related, kinematic and muscular evaluations for gait specific tests, balance and postural control, exercise-specific parameters, mobility tests and muscular parameters; (b) metabolic tests based on cardiovascular, cardiorespiratory and/or ventilatory observations; (c) pain assessment; (d) rates of perceived exertion and fatigue; (e) condition-specific tests and questionnaires; (f) lifestyle and quality of life tests, mental health tests and / or physical activity level; (g) patient self-evaluation and other related tests. Of the 572 eligible articles, 447 (78%) utilized semi-quantitative and qualitative methods while 193 studies combined quantitative analysis with at least one of these 7 groups.

Qualitative summary on wearables for water motion analysis

Only 27 of 572 eligible articles exploited inertial-based wearable devices in studies on aquatic physical activity. The following tables synthesize 23 works in which inertial sensors assessed underwater motion, four remaining studies were excluded from the qualitative synthesis as they exploited accelerometers to evaluate the amount of daily physical activities[27,28] and the quality of sleep[29,30] of subjects undergoing hydrotherapy protocols (Figure 1).

Table 1 summarizes the characteristics and demographics of the included articles, showing that the majority of studies were published between 2017,[31–38] 2019[39–42] and 2020[43–46] and no articles were found before 2014. Most of the articles[31–33,35–37,42,44–51] involved healthy adults or elderly subjects,[41,43] while the remaining investigated anterior cruciate ligament injury,[34,52] incomplete spinal cord injury[39,40,53] and chronic anterior knee pain.[38] Three studies involved a healthy control group,[34,38,39] and one[52] exploited previously published data of a healthy reference group. The sample size was typically 10 or more subjects, up to a maximum of 50, and 4 articles[36,38,44,46] had a balanced gender distribution. One article included both the validation of the developed system as well as observational studies in the clinical field and in sport biomechanics.[34] All studies included observations of motion both on land and underwater, with the exception of [33,47,50,51] in which only underwater motion was investigated.

Table 2 outlines the study purpose, experimental protocols, measured outcomes, wearable technology, a description of additional methods and major study outcomes. The 23 analysed articles encompass a wide variety of study purposes concerning movement analysis, compare land and underwater motion or focus solely on methodological development and validation. This variety is also reflected in the adopted protocols, exercises and evaluation metrics. Gait analysis is performed on dry land and underwater in nine studies,[34,42,43,45–49,51,52] following in four[34,43,48,52] cases the Outwalk protocol.[54] In all of these works, as well as in studies evaluating running on a treadmill,[32,33] the measured outcomes are focused on temporo-spatial parameters, joint kinematics and range of motion. In three studies[37,38,41] squats, split squats and single limb squats have been performed to estimate joint kinematics, range of motion and asymmetries. In the remaining articles, gait initiation,[36,40,53] balance during standing[35,39] and countermovement jumps[50] were included to assess centre of pressure parameters and ground reaction forces. Exercise-specific parameters have been estimated when knee flexion-extension[31] and shoulder movements[44] were performed. Additionally, linear mixed models were developed[43,48] to approximate the effects of water on the observed kinematic parameters. Ground reaction forces were quantified by accelerometer data in[50] and in two studies, quality and validation of algorithms were assessed.[44,46]

Considering wearable methods, 13 studies made use of IMU sensors (gyroscope, magnetometer and accelerometer),[34,35,36,39–41,43–46,48,49,52] 3 used a sensor with accelerometer and gyroscope[37,38,42] and 5 studies applied a stand-alone 3D accelerometer[31–33,47,50]; lastly, Lee and Han[51] explored the novel use of smartphones for underwater gait analysis. The number of devices and their positioning on the subject varied from one to eight, placed most commonly on the trunk and laterally on the lower limbs and in one case on the occipital

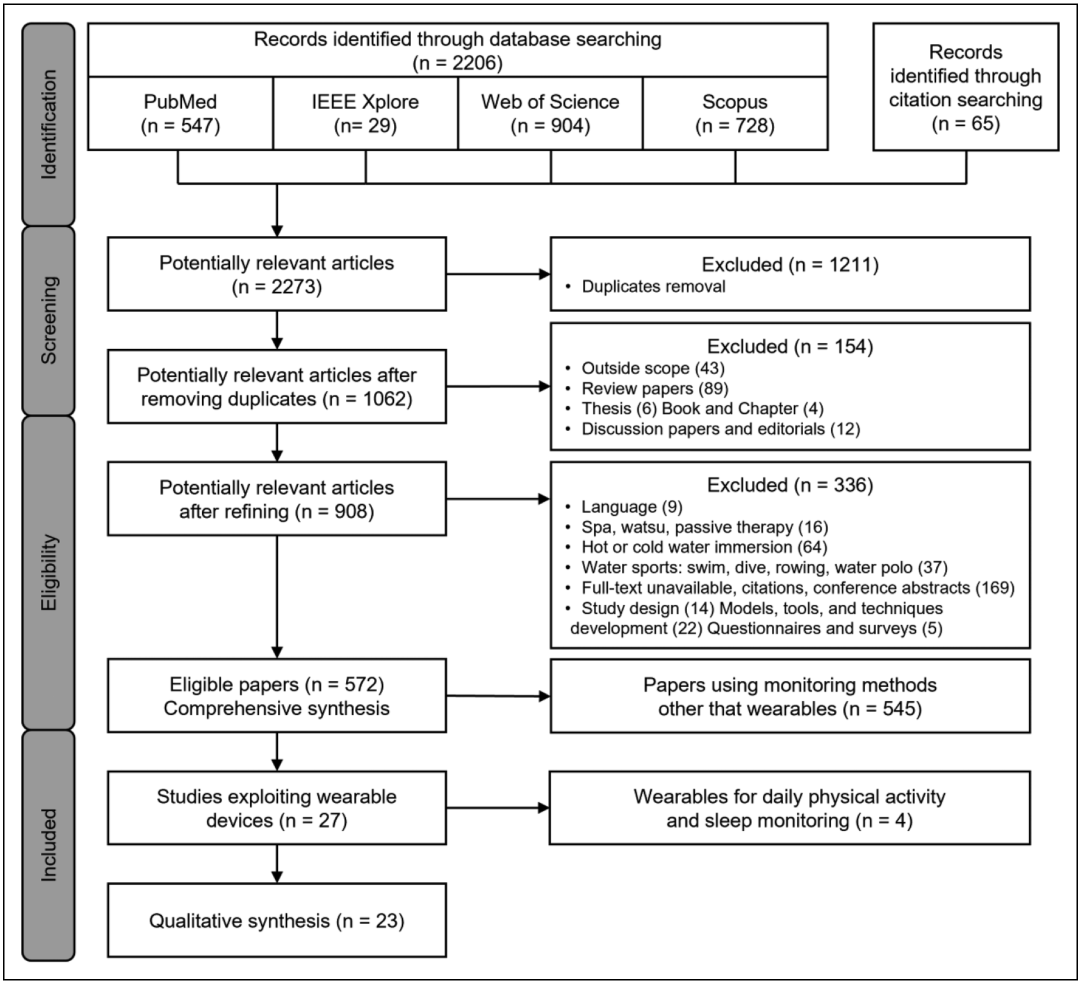

Figure 1. Flow diagram of the identification, screening, eligibility and inclusion steps of the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) systematic literature review process.

region.[47] Notably, only one article investigated the upper limbs.[44] The sensor data sampling rates ranged from 50 Hz to 500 Hz and the waterproofing methods featured in the studies relied mostly on external casings and plastic bags.

Taking into account the use of additional quantitative investigation tools, eight studies exploited wearable devices only.[34,37,38,41–43,48,52,53] Five articles included motion capture and optoelectronic system as support,[45,46,51] reference[32] or as gold standard to validate the inertial sensors.[44,49] Force plates were used by Marinho-Buzelli et al.[35,36,39,40] to estimate the centre of pressure parameters and sway, and by Pacini Panebianco et al.[46] and Chien et al.[50] to determine ground reaction forces. Lastly, Chien et al.,[31] accompanied the accelerometer data with electromyography for the investigation of muscular contraction and near-infrared spectroscopy to estimate the tissue saturation index.

Additional aquatic exercise monitoring methods included metabolic, cardiovascular and cardiorespiratory parameters were investigated using heart rate monitors[31–33,50] and gas analysers.[32,47] No studies were found to include functional or motion-related

Table 1. Review articles demographics. For each selected articles, the first author and publication year, participants investigated (Part), presence of control group (CG), sample size (Sample), gender distribution (M-F) and age are reported. The type of study and the environment investigated is listed in the final column (Measure).

Author	Year	Part	CG	Sample	M-F	Age	Study	Measure
Kaneda et al.[47]	2014	H		50	29-21	27–73	Observational	UW
Fantozzi et al.[48]	2015	H		11	6-5	27.0 ± 3.4	Observational	DL + UW
Cortesi et al.[52]	2016	ACL	H[48]	1	NA	NA	Observational	DL + UW
				(CG 11)				
Chien et al.[31]	2017	H		17	0-17	22.1 ± 0.7	Observational	DL + UW
Macdermid et al.[32]	2017	H		6	NA	29.8 ± 13.0	Observational	DL + UW
Macdermid et al.[33]	2017	H		8	NA	25 ± 12	Observational	UW
Mangia et al.[34]	2017	Elderly	H	5	3-2	71.6 ± 2.2	Validation + Observational	DL + UW
		ACL		1	1-0	39		
				(CG 11)	(CG 6-5)	(CG 27.0 ± 3.4)		
Buzelli et al.[35]	2017	H		10	6-4	NA	Observational	DL + UW
Buzelli et al.[36]	2017	H		10	5-5	19–35	Observational	DL + UW
Severin et al.[37]	2017	H		25	14-11	22.1 ± 4.0	Observational	DL + UW
Severin et al.[38]	2017	AKP	H	20	10-10	22.8 ± 4.0	Observational	DL + UW
				(CG 20)	(CG 10-10)	(CG 22.2 ± 2.9)		
Buzelli et al.[39]	2019	iSCI		6	4-2	42–69	Observational	DL + UW
Buzelli et al.[40]	2019	iSCI		5	4-1	42–69	Observational	DL + UW
Severin et al.[41]	2019	Elderly		24	7-17	71.4 ± 5.4	Observational	DL + UW
Souza et al.[42]	2019	H		1	NA	NA	Validation	DL + UW
Fantozzi et al.[43]	2020	Elderly	H	9	4-5	73.5 ± 5.8	Observational	DL + UW
				(CG 11)	(CG 6-5)	(CG 27.0 ± 3.4)		
Gandoll et al.a[44]	2020	H		2	1-1	20	Validation	DL + UW
Kaneda et al.[45]	2020	H		10	6-4	30 ± 6	Observational	DL + UW
Pacini et al.[46]	2020	H		10	5-5	26.2 ± 3.3	Validation	DL + UW
Monoli et al.[49]	2021	H		7	4-3	NA	Validation	DL + UW
Chien et al.[50]	2022	H		12	0-12	23.6 ± 1.8	Validation	UW
Lee et al.[51]	2022	H		19	7-12	22.0 ± 1.9	Validation	UW
Fantozzi et al.[53]	2022	iSCI		10	9-1	65 ± 8	Observational	DL + UW

ACL: anterior cruciate ligament injury; AKP: anterior knee pain; CG: control group; DL: dry land; H: healthy; iSCI: incomplete spinal cord injury; NA: not available; UW: underwater. An empty cell indicates the absence of CG.

Table 2. Summary of articles included in the review. Organized by publication year, investigation purpose, the exercise protocol followed, the main outcomes and the methods exploited for the analysis of motion. Considering wearable devices, the type of sensor, number and positioning are listed.

Article, purpose	Protocol	Outcome measured	Monitoring methods	Conclusion
Kaneda et al.[47] – Develop model for Energy Expenditure water-walking	Gait UW (3times, 15m, various speed), [W: 1.1m depth, 30°C]	• Energy expenditure estimation (acceleration, velocity, O2 and CO2 exchange)	• A (1: head) • Gas analyser, dry gas meter	Energy expenditure estimation model showed good agreement to the classical measurement both acceleration and speed
Fantozzi et al.[48] – Compare land and water lower limb and thorax-pelvis joints kinematics	Gait DL and UW (3times, 10m, natural speed) [W: 1.2m depth, 28°C]	• Outwalk protocol (temporo-spatial param, joints kinematics) • Linear Mixed Model	• IMU (8: thorax, pelvis, laterally on thighs, shanks, feet)	IMU walking patterns of thorax-pelvis and lower limb joint angles in the sagittal and frontal planes consistent with motion-capture results
Cortesi et al.[52] – Method for land and water gait for joints kinematics analysis of an ACL injured	Gait DL and UW (3times, 10m, natural speed)	• Outwalk protocol (temporo-spatial param, joints kinematics)	• IMU (8: thorax, pelvis, laterally on thighs, shanks, feet)	Water gait can lead ACL patients to increase the knee flexion-extension ROM and improve overall gait patterns
Chien et al.[31] – Estimate impact of land and water knee extension	Three to five knee flexion-extension at various cadences, DL and UW [W: xiphoid depth, 33°C]	• HR, Blood flow, Total Saturation Index • RPE • Muscular activity • Knee extension kinematic	• A (1: below malleolus of the ankle) • HR monitor • Near-Infrared Spectroscopy • RPE Borg's scale • Surface EMG	Faster cadence of water knee extension increases training load (RPE), evoke more muscle contraction, harder cardiac stimulation, and more Total Saturation Index
Macdermid[32] – Compare land and water treadmill running	Treadmill running DL and UW (15min, fixed speed) [W: iliac spine depth, 21°C]	• Transfer function • Temporo-spatial param • Oscillation, shock attenuation, loading rate • Physiological data	• A (3: lateral right tibia, lower back, forehead) • Gas analyser • HR monitor • MC (reference)	Treadmill running in water is a valuable training mode: reduces lower-limb acceleration and shock attenuation, causes slower stride frequency, greater swing time, and increases physiological demand

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Table 2. (Continued)

Article, purpose	Protocol	Outcome measured	Monitoring methods	Conclusion
Macdermid et al.[33] – Evaluate effects of different depth water treadmill running	Treadmill running UW (2.61m/s, 3min) [W depths: mid-shin, mid-thigh, xiphoid, 23.5°C]	• Temporo-spatial param • Rate of impact loading Acceleration features (slope, peak at impact)	• A (1: lateral right tibia) • HR monitor	Progressive depth in UW treadmill running decreases risk of injury due to diminishing impact peak impact accelerations and loading rate at all depths
Mangia et al.[34] – Instrumental validation of IMUs in water, test in clinical and sport settings	Gait DL and UW (three times, 10m, natural speed) [W: 1.2m depth, 28°C]	• Outwalk protocol (temporo-spatial param, joints kinematics)	• IMU (8: thorax, pelvis, thighs, shanks, feet)	IMUs UW had an orientation estimation accuracy of about 6°, lower than gold standard but enough to provide useful information about gait and swimming
Buzelli et al.[35] – Influence of water on COP parameters and on trunk acceleration during quiet standing	Stand still; DL and UW (10 times, 5 eyes open and 5 eyes closed) [W: umbilicus depth, 34°C]	• COP param (time- and frequency-domain) • Trunk acceleration param (postural sway)	• IMU (2: lower and upper trunk) • FP	Aquatic environment may help improve balance control: increases postural instability (bigger COP parameters, larger upper trunk mediolateral acceleration) and changes postural control strategies
Buzelli et al.[36] – Investigate kinematics and kinetics of posture during water gait initiation	5–10s standing and gait initiation; DL and UW (10 times) [W: 1.1m depth, 35°C]	• COP trajectories • GRF components • Trunk acceleration param (postural sway)	• IMU (3: upper and lower trunk, shank) • FP	Water challenges postural control during gait initiation: increases length of COP trajectories, slower execution, larger anterior-posterior mean force and changes trunk acceleration pattern
Severin et al.[37] – Quantify differences between land and water S, SS and SLS	S, SS, SLS; DL and UW (10 times) [W: hip depth, 29.1°C]	• Joints kinematics (ROM, movement depth) • Peak velocities	• A + G (6: laterally on thighs and shanks, trunk, sacrum)	S, SS and SLS in water maintain the movement pattern: does not limit ROM, encourages vertical alignment of body segments, lowers speed, increases movement variability
Severin[38] – Assess kinematics and asymmetry during land and water S and SLS in AKP	S, SLS; DL and UW (10 times) [W: hip depth, 29.1°C]	• Joints kinematics • Asymmetry index score (shank, thigh, thorax)	• A + G (6: laterally on thighs and shanks, trunk, sacrum)	Water S and SLS for AKP increase ROM and asymmetry, suggesting the use of feedback to minimise any movement compensations

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Table 2. (Continued)

Article, purpose	Protocol	Outcome measured	Monitoring methods	Conclusion
Buzelli et al.[39] – Influence of water on quasi-static posture after iSCI	Stand still (10 times, 5 eyes open and 5 eyes closed, DL and UW) [W: umbilicus depth]	• COP parameters • % Body weight offloading • Trunk acceleration param (postural sway) • Perception questionnaire	• IMU (2: upper and lower trunk) • FP • Clinical examination, perception interviews	iSCI in water have larger medians of COP displacement, velocity and area, in both visual conditions. In water, increased trunk accelerations suggest a new postural strategy for balance
Buzelli et al.[40] – Influence of water on gait initiation in iSCI	5–10s standing and gait initiation DL and UW (10 times) [W: 1.1m depth, 34–35°C]	• COP parameters • Trunk acceleration param (postural sway) • Perception questionnaire	• IMU (2: upper and lower trunk) • FP • Clinical examination, perception interviews	Water influences the dynamic postural control during gait initiation prolonging the execution of gait initiation and facilitating longer step execution in iSCI
Severin et al.[41] – Impacts of water on ROM and peak velocities during S and SS	S and SS, DL and UW (10 times) [W: hip depth, 27.3°C]	• ROM trunk, hip, knee • Velocities • S depths	• IMU (6: trunk, sacrum, laterally on thighs, shanks)	Water immersion allow older aged adults greater squat depths and encourages less anterior trunk lean and more hip flexion than on land
Souza at al.[42] – Analyse walking inside and outside water	Gait DL and UW (8m, natural speed) [W: sternum depth]	• Temporo-spatial param	• A + G (4: inner side calf, medial malleoli)	The prototype presented good performance in gait evaluation in water
Fantozzi et al.[43] – Investigate land and water walking kinematics of elderly and young adults	Gait DL and UW (3 times, 10m, natural speed) [W: 1.2m depth, 28°C]	• Outwalk protocol (temporo-spatial param, joints kinematics) • Linear mixed models	• IMU (5: trunk, pelvis, laterally on thigh, shank, foot)	Healthy elderly had specific gait patterns in water, different from young adults influenced not only by speed and age, but also by the interaction between the two variables
Gandolla et al.[44] – Design a biofeedback for aquatic	Shoulder movements	• Measurement	• IMU (3: trunk, upper and lower arm)	Setup for underwater real-time human motion and biofeedback have been

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Table 2. (Continued)

Article, purpose	Protocol	Outcome measured	Monitoring methods	Conclusion
movement analysis based on a multi-joints network of IMUs		uncertainty and algorithm validation • System usability	• Optoelectronic (land validation)	designed, produced, validated and tested demonstrating feasibility and usability with recorded good system usability evaluation
Kaneda et al.[45] – Compare land and water walking using IMU and video camera	Gait DL and UW (three times, three speeds, 10m) [W: 1.35m depth]	• Stance ratios and joints kinematics • Acceleration, angular velocity	• IMU (1: thigh midpoint front) • MC	During walking in water, acceleration and impact force, which burden the thighs or knees just before the heel contact, are reduced
Pacini et al.[46] – Water performance of 17 algorithms for land gait events estimation	Gait DL and UW (10m, five times, natural speed) [W: 1.2m depth, 28°C]	• Quality algorithms • Temporo-spatial param • GRF	• IMU (5: trunk, shanks, dorsal feet) • MC • FP	No proposed algorithm can be generally preferred over the others. Angular velocity-based algorithms with sensors on lower limbs result more reliable than acceleration-based, but not as accurate and repeatable
Monoli et sl.[49] – Test and validate developed underwater wearable IMUs	Gait DL (6 times) and UW (11 times, natural speed)	• Knee angle • Gaussian Process Regression enhancement	• IMU (2: laterally on thigh and shank) • MC • Optoelectronic (land validation)	The proposed IMU system is suitable for use on land and underwater to evaluate the knee angle during the gait
Chien et al.[50] – GRF measure and prediction in different accelerometer positions and jump intensities	UW countermovement jumps at different \% HR reserve [W: 1m depth, 31–33°C]	• Acceleration • GRF • GRF predicted via accelerometer data	• A (3: right ankle, lumbar, neck) • FP • HR monitor	The resultant acceleration measured at C7 was identified as the valid estimated GRF for body weight on land for jumping skeletal loading in water
Lee et al.[51] – Reliability of leg segment and joint	Gait UW (at least 14 steps) [W: 1.1m depth, 33°C]	• Joints kinematics and ROM (hip, knee)	• IMU (3 smartphones: frontal on trunk, thigh, and shank)	Smartphones provide reliable measurements of leg segments and

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Table 2. (Continued)

Article, purpose	Protocol	Outcome measured	Monitoring methods	Conclusion
angles measurements with smartphones			• MC	joint angles during aquatic gait and are a relatively affordable option
Fantozzi et al.[53] – Compare gait initiation on iSCI subjects dry land and in water	Gait initiation DL and UW [W:1.2m depth, 30°C]	• Anticipatory Postural Adjustment time • First-step characteristics	• IMU (4: upper and lower trunk, left and right shanks)	In water is measured and increased first step duration and a decreased root mean squared acceleration for upper and lower trunk in the medio-lateral and anterior-posterior direction, respectively.

A: accelerometer; AKP: anterior knee pain; COP: center of pressure; DL: dry land test; EMG: electromyography; FP: force platform; G: gyroscope; GRP: ground reaction forces; HR: heart rate; IMU: Inertial Measurement Unit; iSCI: incomplete spinal cord injury; MC: motion capture; ROM: range of motion; RPE: rate of perceived exertion; S: squats; SS: split squats; SLS: single limb squats; UW: underwater; W: Water, characteristics of the pool.

tests, pain assessment or lifestyle and quality of life questionnaires. However, the rate of perceived exertion was evaluated by Chien et al.[31] using Borg's scale and Marinho-Buzelli et al.[39,40] performed a clinical examination on balance and perception via International Standards for Neurological Classification of Spinal Cord Injury, Berg's Balance Scale and Mini-BESTest and perception interviews.

The critical assessment of the selected articles is provided in Table A3, and summarizes the answers to the custom questionnaire (Table A2). The analysed studies were generally found to be of satisfactory value, since most of the inquiries were marked as present or partially answered. Nonetheless, it is worth noting that four questions received mostly negative answers. The articles did not specify the study design (question 1), with the exception of two case series,[39,40] a case study[52] and a cross-validation study.[47] Similarly, the study participants and inclusion/exclusion criteria were not clearly justified (question 9), apart from[38] which involved a gender-matched control group and[51] that conducted a power analysis to justify the number of subjects involved. Additionally, none of the studies included multiple measurements over a complete rehabilitation protocol (question 7), nor did any studies address the management of missing data (question 15).

Discussion

The synthesis of eligible articles addressed the first research question of this work, pointing out that the most frequent methods applied to perform aquatic motion analysis are dynamometers and force plates, followed by motion capture. Furthermore, it was possible to clearly differentiate between two major methodological categories: quantitative methods providing an objective evaluation of motion and qualitative or semi-quantitative methods to evaluate the quality of motion and the effects of water exercise across a scaled spectrum.

It is important to note that the current review did not distinguish between studies that evaluated motion underwater, on land or in both environments but considered all the methods exploited to assess motion in the context of aquatic exercise. The authors also wish to point out the limitations of this systematic review as the chosen keywords and inclusion criteria may have excluded some relevant studies. This review did not consider wearable sensors for swimming monitoring, choosing instead to focus on the investigation of water exercises. In contrast to Marinho et al.[21] which focused on defining the benefits of wearable technologies, this review identifies the research gaps and provides concrete suggestions to improve future aquatic exercise monitoring studies.

The second research question of this work focused on identifying major gaps in studies using wearable devices for monitoring of underwater exercises and making recommendations on how to improve aquatic motion analysis. Four major research gaps have been recognized. First, the absence of clinical protocols for underwater motion analysis studies. While the quality assessment indicates that the studies are of overall good quality, a lack of common methodologies renders the cross-comparison of study findings infeasible. Each article defined and used a distinctive protocol exploiting wearable devices, both in terms of number of sensors used and their placement on the body. Even when the task executed was similar, the study objectives, methods and outcomes varied greatly between studies. Future works may wish to define clear protocols for underwater wearables and allow for the quantitative comparison of water physical activities with increased confidence.

The second major research gap found is the substantial deficit of whole-body studies via wearable devices. This restriction is likely due to the technical difficulty of inertial sensor data analysis, especially in the water environment where standard methods do not exist. Focusing on a limited portion of the body, however, does not allow for the explicit consideration of the effects of drag and buoyancy as additional forces unique to the water environment.

The lack of longitudinal studies monitored via wearable devices was identified as the third main gap. All articles included in the qualitative synthesis had a maximum of 10 repetitions of the selected task, performed in one day and most of them included only healthy subjects. This may be due to the challenges associated with organizing repeated measures with wearable devices, resulting in limited insight into the influences of water on kinematic features as well as the effectiveness of long-term hydrotherapy.

The fourth gap identified a need for measurement and assessment methods specific to aquatic exercises, as studies remain heavily reliant on the use of land-based methods. When motion capture systems[32,44,45,49] or other sensing modalities[31,35,36,39,40,46,50] were used, they were nearly universally applied for cross-comparison or validation of a newly proposed method and data were infrequently related with wearable sensors data. Only a single study[46] combined multiple sensor data to improve motion assessment. Furthermore, only seven studies exploited additional methods for metabolism monitoring. A combined approach using multiple quantitative methods and the involvement of specific tests and questionnaires may improve the current interpretation of aquatic exercise and the effects of the water environment on kinematics.

The major finding of this review is that there is a substantial deficit of protocols and wearable monitoring methods for aquatic exercises. Specifically, we advocate for the establishment of common protocols for wearable sensor placement and whole-body monitoring during non-recreational aquatic exercise. Furthermore, we encourage longitudinal studies which include multiple sensing modalities to generate a more complete understanding of the effects of aquatic exercises on kinematic parameters.

Clinical messages

- There is a lack of clear protocols for the use of wearable devices in underwater motion analysis, hindering the cross-comparison of studies.
- Longitudinal studies monitored via wearable devices are necessary to estimate the effects of long-term aquatic exercises on kinematic parameters.
- Incorporating wearable sensing technology into long-term hydrotherapy programmes may improve monitoring processes and the cross-comparison of study outcomes.

Author's contribution

CM: Study design, data collection, analysis and interpretation and preparation of the manuscript.
JAT: Analysis and interpretation, preparation and revision of the manuscript.
LP: Study design and manuscript revision.
MG: Study design, interpretation of data and manuscript revision.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research was funded by the Estonian Centre of Excellence in IT (EXCITE) and European Regional Development Fund.

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Appendix

Table A1. Summary of the literature source databases and corresponding keywords used in this systematic review. For each database, the number of articles included after screening is provided.

		PubMed[a]	IEEE Xplore	Web of Science[b]	**Scopus**[b]
Underwater OR water OR aquatic	(rehabilitation OR exercise OR kinematic OR therapy OR training OR hydrotherapy OR hydrokinesitherapy) AND (wearable OR sensor)	15	8	28	26
	treadmill OR walk OR gait	325[c]	5[c]	651	410
	wearable	10	4	10	12
	IMU OR accelerom* OR inertial	18	3	28	36
	EMG OR electromyog*	92	4	93	133
	motion capture OR camera	22	4	10[d]	8[d]
	force plat*	36	0	40	52
	dynamom*	24	0	33	40
	gonio*	5	1	11	11
	Total	547	29	904	728

[a]Additional filters: English AND Human.
[b]Additional filter: English.
[c]Additional keyword run: ((underwater) OR (aquatic) OR (water)) AND ((treadmill) OR (walk) OR (gait) OR (run)).
[d]Only motion capture: ((underwater) OR (aquatic) OR (water)) AND (motion capture).

Table A2. List of questions used in the quality assessment. Questions are based on the STROBE checklist, CASP appraisal tool and the McMaster Quality assessment instrument.

Topic	Q	Questions
		Characteristic of the articles
Study design	1	Is the study design described with commonly used terms?
Novelty	2	Are the novelty and significance of the articles described in the introduction?
		Introduction
Background	3	Are the scientific background and rationale for the investigation reported and properly referred?
Objectives	4	Are the objectives of the study clearly described?
	5	Are the research hypotheses or research questions stated?
		Method
Setting	6	Are the procedures, settings and locations described? (exercises protocol, environment characteristics)
	7	Is it considered a long-term protocol with repeated measurements over multiple weeks? Are measures taken pre/post intervention, or only one time?
Participants	8	Are the characteristics of the participants described? (age, gender, status, condition) Are the inclusion/exclusion criteria expressed?
	9	Is the size of the population justified? For matched studies, are matching criteria provided?
Instruments	10	Is the wearable method clearly described? (placement, number of sensors and physical and sensor characteristics)
	11	Is the wearable sensors-based protocol clearly described or referenced? (data extraction and data processing)
	12	Are any additional investigation methods applied? Is the comparison performed with a reference method? If yes, are they clearly described and referenced?
Variables	13	Are the main investigated features and outcomes clearly described?
Statistics	14	Are the statistical methods used described and justified?
	15	Is there a description of the missing data and their management?
		Results and Discussion
Results	16	Are the main findings clearly stated? Are the probability and confidence intervals stated? Is the accuracy of the measure estimated?
Limitations	17	Are the limitations of the study expressed, taking into account sources of potential bias or imprecision?
Interpretation	18	Are an overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidences provided?
Significance	19	Are the general validity of the study and significance of the study results for the scientific community and future studies mentioned?

Table A3. Methodological quality assessment results following the questions listed in Table A.2: (1–2) Characteristics of the article, (3–5) Introduction, (6–15) Method and (16–19) Results and Discussion. Possible answers: present (P), absent (A), partially present (PA) and not applicable (NA).

Article	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Kaneda et al.[47]	P	P	P	P	A	P	A	P	A	A	P	P	P	P	A	PA	P	P	P
Fantozzi et al.[48]	A	A	P	P	A	P	A	P	A	P	P	A	P	P	A	P	P	P	P
Cortesi et al.[52]	P	PA	P	P	A	PA	A	P	NA	P	P	A	P	A	A	P	A	P	A
Chien et al.[31]	A	P	P	P	A	P	A	P	A	PA	A	P	P	PA	A	P	P	P	P
Macdermid et al.[32]	A	P	P	P	P	P	A	P	A	P	P	P	P	P	A	P	A	P	A
Macdermid et al.[33]	A	PA	P	P	A	P	A	P	A	P	PA	P	P	PA	A	P	A	PA	A
Mangia et al.[34]	A	PA	P	P	A	P	A	P	A	P	P	A	P	P	A	P	A	P	P
Buzelli et al.[35]	A	PA	P	P	P	P	A	PA	A	P	P	P	P	P	A	P	P	P	P
Buzelli et al.[36]	A	P	P	P	P	P	A	P	A	P	P	P	P	PA	A	P	P	P	P
Severin et al.[37]	A	PA	P	P	P	P	A	P	A	P	P	A	P	P	A	P	P	P	PA
Severin et al.[38]	A	P	P	P	P	P	A	P	PA	P	P	A	P	P	A	P	A	P	P
Buzelli et al.[39]	P	A	P	PA	A	P	A	P	NA	P	P	P	P	PA	A	P	P	PA	P
Buzelli et al.[40]	P	A	P	PA	A	P	A	P	NA	P	P	P	P	PA	A	P	P	PA	P
Severin et al.[41]	A	PA	P	P	P	P	A	P	A	P	P	A	PA	P	A	P	P	P	PA
Souza et al.[42]	A	PA	P	P	A	P	A	A	A	P	P	A	P	A	A	PA	PA	PA	P
Fantozzi et al.[43]	A	A	P	P	P	P	A	P	A	P	P	A	P	A	A	P	PA	P	A
Gandolla et al.[44]	A	P	P	P	A	P	A	PA	A	P	P	P	PA	P	A	P	A	P	P
Kaneda et al.[45]	A	A	P	P	A	P	A	P	A	P	P	P	PA	P	A	P	P	P	P
Pacini et al.[46]	A	P	P	P	A	P	A	P	A	P	P	P	P	P	A	P	P	P	P
Monoli et al.[49]	A	P	P	P	P	PA	A	PA	A	P	P	P	P	P	A	P	P	P	P
Chien et al.[50]	A	P	P	P	A	P	A	P	A	P	P	P	P	P	A	P	P	P	P
Lee et al.[51]	A	P	P	P	A	P	A	P	P	P	PA	P	PA	PA	A	P	P	P	PA
Fantozzi et al.[53]	A	PA	P	P	P	PA	A	P	A	P	P	A	P	P	A	P	P	P	P