Motivation, Methods and Progress Towards Underwater Gait Assistance Robots

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December 12, 2024

Abstract

This paper investigates the motivations for developing underwater gait assistance robots and explores methods that leverage the benefits of partial submersion for rehabilitation. An overview of the current state of underwater gait rehabilitation robots is provided, highlighting the successes and limitations of existing designs. The study surveys key approaches in gait characterization, actuation, sensing, system modeling, and control strategies to identify those best suited for underwater environments. Emphasis is placed on how buoyancy and drag can be harnessed during hydrotherapy to improve gait rehabilitation outcomes. The review identifies research gaps and outlines future opportunities for designing effective underwater robotic systems that complement therapeutic needs.

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***Abstract*—This paper investigates the motivations for developing underwater gait assistance robots and explores methods that leverage the benefits of partial submersion for rehabilitation. An overview of the current state of underwater gait rehabilitation robots is provided, highlighting the successes and limitations of existing designs. The study surveys key approaches in gait characterization, actuation, sensing, system modeling, and control strategies to identify those best suited for underwater environments. Emphasis is placed on how buoyancy and drag can be harnessed during hydrotherapy to improve gait rehabilitation outcomes. The review identifies research gaps and outlines future opportunities for designing effective underwater robotic systems that complement therapeutic needs.**

***Index Terms*—hydrotherapy, gait assistance, mechatronics, robotic rehabilitation**

I. Introduction

BOTH physical and neurological disorders can lead to measurable changes in the gait of a person [1]. While these changes may help the clinician to identify what problems a person is facing, for a person, it can lead to pain, disability, loss of movement and independence, increased fall risk [2], and other issues. It is, therefore, important to develop methods to help a person restore mobility and gait as much as possible while keeping a person safe. One popular approach is gait training, where a person is encouraged to perform tasks with appropriate supports that are designed to help their body regain motor function that was impaired. While gait training is also used to increase the proficiency of healthy individuals during physical training, its application to people suffering from external disabilities such as stroke, spinal cord injury, or age-related complications presents a more nuanced challenge, as one has to balance the benefits of increased physical training with the risk of further aggravating the condition of a person if they are asked to perform a task that is not medically advisable for them. It is therefore important to carefully choose what tasks a person has to perform, to what extent they should exert themselves, and what movements they should avoid.

Recently, robotic platforms and devices have been deployed to help with gait training. Robotic systems are precise and carefully calibrated, which makes them well-suited to address the problems faced during gait training detailed above. In addition, since most robotic platforms are equipped with a wide array of sensors, they can help the clinician carefully assess the progress of a person while also making sure that a person is not crossing any thresholds of danger during their training. Various devices have been developed using different approaches to solving these problems. However, most of these devices are designed to work over ground in dry environments.

Partial submersion in water is an obvious method to provide Body Weight Support (BWS). Still, it also introduces the effects of drag, which may perform a function equivalent to resistance training. Hydrotherapy is becoming a more common method for helping gait rehabilitation of post-stroke victims [3]. Hydrotherapy is largely used as a standalone intervention method. However, it may be possible to design systems that leverage the beneficial effects of submersion to create compliant but effective gait intervention programs. Yet most robotic platforms are not well suited to be used underwater to support hydrotherapy.

In this paper, the different types of gait disorders and their causes are briefly outlined. Hydrotherapy is introduced as a method for improving gait. The current state of the art of underwater gait devices will be presented. The objective of this review is to identify the advantages that hydrotherapy offers over other forms of gait training, identify what kinds of active systems will specifically maximize these benefits, and explore what may be the best choices in terms of control strategies for such systems. The conclusion presents avenues for developing these devices and control strategies.

II. Motivation - Gait Disorders

Baker [1] and Pirker and Katzenschlager [4] outline the different physiological impairments that can lead to observable changes in gait. Jun et al. tracked the simulated differences caused by some common gait disorders using a Kinect motion-tracking system and foot pressure data [5]. Some examples are shown in Fig. 1. The two types of gait disorders commonly addressed by gait training are those caused by musculoskeletal problems and those caused by neurological damage. Specifically, there is a focus on disorders whose treatment might benefit from body weight support and slower movement speeds in an underwater setting.

A. Disorders affecting muscles

Depending on which muscle or group of muscles is affected, there may be differing visible changes to kinematics. A waddling gait may manifest if there is weakness in the proximal

This work was supported by the National Science Foundation through grant number CMMI-2024409. *(Corresponding Author: Frank C. Sup IV)*

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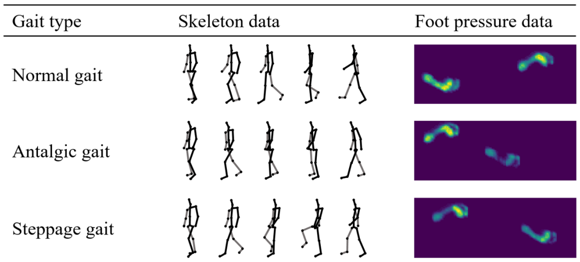


Fig. 1: Simulated differences in kinematics and foot pressures between normal gait and common gait disorders. [5]

muscles that stabilize the hip during the swing phase. A person may display increased side-to-side trunk movement.

Steppage gait or foot drop is caused by a weakness of ankle dorsiflexion. It manifests as the inability of a person to lift their toes from the ground during the swing phase. It may also cause a person to raise their hip higher than usual to compensate and not trip over obstacles [6], [7].

An antalgic gait is a gait that develops as a way to avoid pain while walking (antalgic = anti- + alge, "against pain"). It is a form of gait abnormality where the stance phase of gait is abnormally shortened relative to the swing phase. It is a good indication of weight-bearing pain [8]. On the other hand, in a coxalgic gait, the pain is present on one side of the hip. The upper trunk is shifted to the affected side to reduce the muscle forces during walking [8]. Finally, Knee hyperextension is caused by weakness in the quadriceps muscles [8].

Gait training can address musculoskeletal impairments by allowing a person to rebuild the strength of specific muscles. Disorders caused by muscle weakness, such as waddling and foot drop, would benefit from body weight support underwater. Actively controlled assistive devices that can apply targeted forces at specific points in the gait cycle to allow a person to maintain gait while they are training their muscles.

B. Disorders caused by neurological damage

Neurological damage is commonly caused by stroke, and symptoms depend on which part is affected. However, it may also be caused by other disorders such as Parkinson's disease. Ataxic gait is characterized by uncoordinated and irregular movements during gait. A person often widens their stance to increase the size of the support polygon. There are a wide variety of injuries to the brain or spinal cord [9], or to the proprioceptive system (identified by a further worsening of gait when the eyes are closed [10]) that may lead to such a gait.

Spastic gait consists of an increase in muscle spasticity caused by cerebral palsy, cervical spondylotic myelopathy, or multiple sclerosis. It may lead to a person holding the affected leg in extension and plantar flexion. In case both legs are affected, "scissoring" may be observed, and the footsteps of a person are observed to be very close to each other.

Among the most common gait impairments observed in the elderly, Parkinsonian gait has a decrease in both step length and step height [11], leading to the appearance of shuffling. It may even lead to reduced motion of the upper body and the arms and is often observed asymmetrically at first. One possible symptom is festination, where the steps become rapid and short and take on the "appearance of running" [1]. The CoP of a person moves to the front of their support polygon, making it harder for a person to maintain balance.

Presenting as a combination of some of the previous gait patterns, people suffering from damage to the frontal lobes [12] may exhibit both reduction in movement and increased instability. Even freezing might occur.

Gait training can help a person practice coordinating different movements required to successfully execute a stable gait. However, some types of impairment, such as festination, may not be suited for underwater treadmills. The increased drag might make it harder for people who tend to make quicker movements to balance themselves. For the disorders that require retraining muscle coordination, some form of active force modulation would be required underwater, which is a strong motivation for developing active underwater gait assistance devices.

Other abnormal gaits such as freezing, Dystonic gait, Choreatic gait, Myoclonic gait, etc [4] are unpredictable and erratic and therefore do not lend themselves to the current discussion.

III. Gait Treatment Overview

Various approaches have been tried depending on the cause and manifestation of the impairments listed in Section II. Lam et al. [13] and Belda-Lois et al. [14] provide an overview of the different systems in use and current literature that exists regarding their efficacy for spinal cord injury and stroke, respectively. Many of these systems can be used in conjunction with each other and are not mutually exclusive, and some are discussed in Section VII. Gait training is a very common treatment, especially for mild impairments.

A. Exercise Therapy

Exercise therapy is one of the most common forms of gait rehabilitation treatment [15] due to the unlikeliness of extreme adverse effects on the patient. The scope of exercise therapy is large, ranging from walking under supervision to training specific muscles [15]. Van Peppen et al. found greater evidence for the benefits of task-oriented exercise training when it is used soon after stroke and in an intensive manner than for other methods of rehabilitation [16]. Even so, the observed improvements did not greatly change the quality of the patient's gait [17].

Lower extremity strength training is a relatively less common form of exercise therapy, but some studies do present strong evidence for improvement in gait speed after such activity [18]. Another novel method is Motor Imagery Practice, where a person is asked to visualize certain situations while performing the therapy, such as catching a bus [19]. Pilot studies indicate that there may exist benefits to such methodology [19], [20]. Belda-Lois et al. provide an overview of the different Neurophysiological techniques used post-stroke [14].

B. Treadmill Gait Training

Treadmill gait training is an attractive form of rehabilitation therapy because it is repeatable and controlled. In addition, it allows for more easily integrating Body Weight Support (BWS). In keeping with the results for exercise therapy, the benefits seem to be more pronounced when the treadmill is operated at higher speeds [21]. The efficacy of different degrees of BWS is contested, but the Ottawa Panel does suggest its use [22] for stroke victims.

Treadmill training and BWS are perhaps even more popular for individuals with spinal cord injury (SPI) because they avoid having to apply loads to their spinal cords. It is beneficial when used under supervision for some classes of SPI people [23].

C. Robotic Devices

As noted in Section I, the main motivation for integrating robots into gait treatment protocols is the repeatability and precision with which they can be operated. Robotic devices can be used in conjunction with many of the techniques mentioned previously. Specifically, BWS lends itself for use with robotic systems due to the reduced strain on the clinician and increased repeatability. However, existing literature has both supported [24], [25] and questioned [26], [27] the efficacy of these devices.

Various approaches have been used to design gait assistance robots in terms of both design and motivation. This is especially important when considering what other methods the robotic device is meant to supplement. To this end, the different design approaches that are commonly used are compared regarding their applicability to underwater use in Section VI.

IV. Gait Hydrotherapy

Hydrotherapy is considered one method of aiding the rehabilitation of an individual after stroke [3]. The immediate appeal of submerging a person is the apparent reduction in the weight of body parts due to buoyancy. Still, there are other effects, like drag, that need to be considered. These effects can be amplified or modulated using different kinds of devices. Some of these ideas are explored here.

A. Effect of submersion

Barela et al [28] and Carneiro et al [29] study the different effects of walking underwater that differentiate it from over ground walking. Barela et al. measured a significantly lower self-selected walking speed when a person walked underwater (mean 0.5 m/s vs 1.39 m/s). There was no notable difference in the percentage of gait spent in the support phase.

Both papers noted a reduction in the ground impact forces. This is not surprising as the reduced effective weight of the body and the reduced speeds of walking would both support this. Barela et al. also measured the EMG signals during both gaits and noted that there was persistently higher excitation for all muscles except the gastrocnemius medialis underwater. While muscle excitation and activation are not equivalent [30], a more persistent excitation would suggest that the body is attempting to carry out stronger tetanic contractions. Both papers report that the posture of a person was straighter underwater, with both knee and hip extensions being greater during stance.

B. Positive effects of hydrotherapy

Based on the previously noted differences in underwater gait, it would be natural to assume that there are some advantages to hydrotherapy for gait rehabilitation. The most compelling evidence is for increased cardiovascular fitness and muscle strength [3], [31], which, while not a direct objective of gait training, is certainly beneficial to a person's recovery. On the other hand, it is inconclusive whether or not training underwater leads to higher gait speeds for overground walking in the long term [31], [32]. The increased flexion in the joints noted previously may also have beneficial effects for increasing the range of movement of the people. While long-term studies about the effects of hydrotherapy are not abundant, the current research does not indicate any negative effects on a person.

C. Effect of devices

The effects of being underwater can be amplified or subdued using different devices. These devices range from bodies attached to different body parts influencing the force due to their effective weight to actively controlled devices.

1) Passive Devices:

a) Increased weight: Weighted cuffs can be added at different points on the leg to change the gait dynamics. Increased weight can modulate the effect of buoyancy on the human body. Studies carried out with cuff weights have noted effects on the peak flexion angles of the leg and correspondingly on the duration spent in each phase of the gait.

Multiple researchers have observed an increase in the amount of time that a person spends in the support phase when they are wearing weights [34], [35] although all of them note that the change is not very large. Jung et al. state that the difference disappears with a Bonferonni correction, which has been criticized for being overly conservative [36]. Pereira et al. observed minimal differences in their tests on hemiparetic people [33].

With the weight installed, there is reduced hip flexion on the leg [33], [34]. This is hypothesized to be because of the reduced "floating" effect at the end of the forward swing. Jung et al. observed this effect for both ankle and knee weights. Nishiyori et al. observed a small increase in speed after putting on the cuff weights [35], and this was confirmed by Pereira et al. [33], with the weight on the non-paretic limb having a greater effect.

b) Reduced weight: The effective weight of a limb segment can also be reduced by attaching a buoyancy cuff. The resultant dynamics are in many ways opposite to those of weights. A significant increase in knee flexion was observed, especially when the cuffs were installed on the non-paretic leg [33]. This indicates that they made it easier to lift the leg post-toe off. When cuffs were used on both legs, there was a reduction in the double support phase [33]

Parameter	Normal Aquatic Gait	Weights on both legs	Cuff (Unaffected Leg) Weight (Paretic Leg)	Cuffs on both legs	Cuff (Paretic Leg) Weight (Unaffected Leg)
Gait Speed (m/s)	0.27 (0.08)	0.32 (0.09)	0.30 (0.08)	0.27 (0.08)	0.28 (0.09)
Stance Phase (% gait cycle)	65.6 (6.8)	6402 (6.5)	65.2 (8.1)	59.4 (7.3)	59.2 (7.2)
Step length (cm)	23.0 (8.2)	23.5 (7.2)	22.1 (7.2)	24.8 (8.5)	28.6 (7.6)

TABLE I: Effect of adding weights or buoyancy cuffs to the legs of people with hemiplegia [33]

It is reasonable to assume from the above results that if one was able to dynamically modify the effective weight of different limb segments, they could have an observable effect on the gait of a person. The results obtained by Pereira et al. are summarized in Table I.

2) Active devices: At present, there are not many active underwater gait rehabilitation devices. The existing ones tend not to use motors, instead preferring pneumatic actuators [37] [38]. Motorized actuators have been used for other applications such as breaststroke assistance [39]. This particular device used motion information from IMUs and position information from the Bowden cable that was used to power the device to apply a force supporting the "sweep phase" of the breaststroke. They observed a reduction in the intensity of EMG signals using the system. While it is designed for a different motion, this work demonstrates a working underwater human-robot interaction system where the control system relies on data from a person to initiate the powered motion. The devices that have been developed for underwater gait assistance have a higher dependence on the periodicity of gait, as discussed below:

a) Underwater Robotic Gait Trainer(RGTW) [37]: The RGTW developed by Miyoshi et al. uses 10 off-the-shelf pneumatic actuators to support hip extension and flexion and knee extension and flexion. The control system was a position controller that attempted to replay a recording of a person's unperturbed underwater gait. The only other sensor used was a foot switch to detect foot contact. A comparison of a person's gait with and without the device showed a reduction in the strength of EMG signals in lower body muscles. As this device does not attempt to modify the gait of a person, it is difficult to evaluate its effectiveness in gait rehabilitation.

b) Soft Sensorless gait assistive suit [38]: This gait assistive device developed by Miyazaki et al. uses custom-made artificial muscles to support knee and hip flexion. To detect when to activate the support, they monitor the derivative of the pressure in the chambers, waiting for it to cross a threshold value. However, the sensor is only active at certain periods between a "non-detection time" (38-91% of the gait cycle). Therefore, there is a restriction on the speeds that a person can walk at. Testing indicated slightly greater knee flexion and walking speeds.

c) Leg Movement Apparatus [40]: The LMA developed by Miyoshi et al. is powered by the arms of a person like that of an elliptic bicycle. It is, therefore, unclear whether it is a passive or active device. The device uses a four-bar linkage to kinematically connect arm and foot movement. In addition, there is a spring-loaded to generate the "kick-off" at the end of the stance phase, which introduces some hysteresis to the motion of the footplate. The authors noted greater knee, hip, and ankle flexion using the spring, but comparisons of EMG profiles were inconclusive.

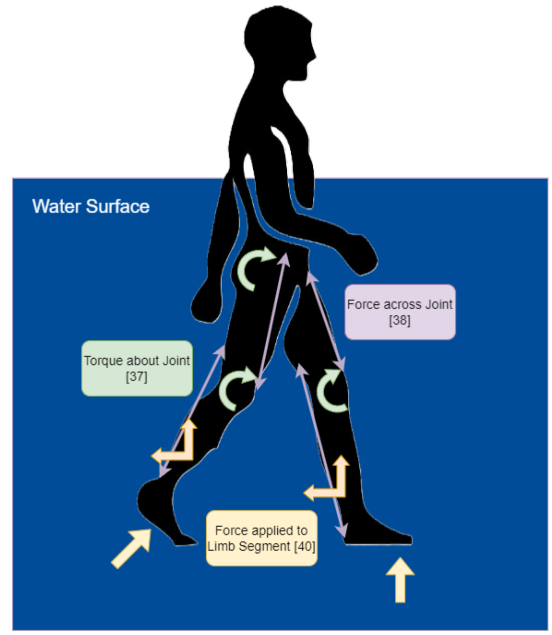


Fig. 2: Three modes of assistance in underwater gait intervention devices

The methods used by these devices are summarized in Table II

We observe that there are a few different methods which can be used to apply forces to the human body during gait, as demonstrated by these designs. These methods are summarized in Fig. 2, along with references to the papers that discuss them.

From this review, the current range of robotic underwater gait devices is limited and has not been explored sufficiently. In the rest of this paper, we will review different approaches to designing an underwater gait assistance device and explore which methods hold the most promise for this specific application. The components focused on, and their relationships are shown in Fig. 3.

V. Gait Characterization

To have a better understanding of the effectiveness of different systems in helping people to redevelop healthy gait, it is important to have clear metrics that can quantify the differences in gait pre- and post-intervention. While it is possible to analyze EEG [41] or electromyography (EMG) [42] or even to simply observe the walking patterns of a person and judge

Device	Authors	Gait characterization method	Actuators	Sensors	System Model	Control Strategy
Underwater Robotic Gait Trainer [37]	Miyoshi et al	Lower limb EMG	Pneumatic Actuation	Encoders, Foot switch	None	Position Control
Soft Sensorless gait assistive suit [38]	Miyazaki et al	Gait kinematics	Pneumatic artificial muscle	Back pressure monitor	State space machine	PID control of pressure
Leg Movement Apparatus [40]	Miyoshi et al	Gait kinematics	Upper body	None	None	None

TABLE II: Summary of the methods used by current underwater gait assistance devices

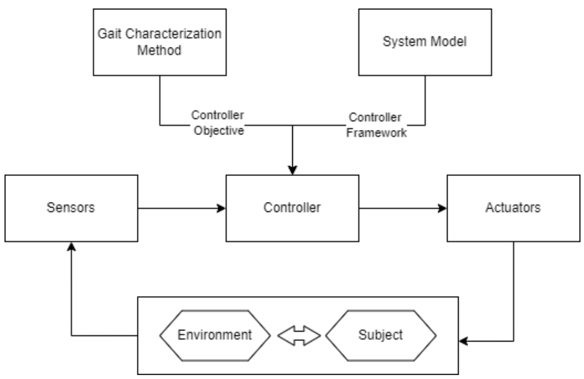


Fig. 3: Components of a gait intervention robot design as explored in this paper

whether the treatment is having a positive effect or not, this usually requires the presence of a clinician who can provide expert insight. Having a numerical quantification of the health of an individual's gait can aid technicians in tuning their systems. It may be specifically useful when designing robots if one wishes to use learning-based methods that require a cost function to optimize. We, therefore, review some of the methods that are used to quantify gait quality.

A. Clinical Measures

O'Sullivan and Schmitz describe many tasks that a clinician can use to determine the recovery progress of a patient [43]. However, most of these tasks involve a person following specific instructions and cannot be evaluated actively while they are practicing gait. The ICF does suggest gait pattern measures (b770) as one of the parameters of healthy gait [44]. However, Krasovsky and Levin point out that considering only the parameters individually would go against the ICF's methodology for prescribing these tests as they can be thrown off by compensatory movements by a person without an increase in coordination [45].

B. Biomechanical parameters

Roberts and Prince present an extensive review of the different kinematic and dynamic parameters that can be tracked to determine the health of an individual's gait post-stroke [46]. They specifically focus on how often each parameter is used in papers and whether any statistical significance is demonstrated in favor of any measure, assigning them a "level of evidence". Their findings indicate that power, work, and energy parameters were the most commonly used measures, which is supported by the work of Sagawa et al. [47]. This includes hip power, knee power, total energy expended, etc. However, the most commonly reported single primary measure was walking speed. This is perhaps because this parameter is easy to measure and indicates other measures such as step length, walking cadence, and step height [48].

C. Spatial measures

Spatio-temporal parameters have a degree of consistency for individuals across different tests [49]. One of the common ways to present this data is through cyclograms that plot two joint angles against each other [50]. It has been shown that cyclograms can distinguish between healthy and hemiparetic gait [51]. However, in themselves, they are qualitative rather than quantitative measures of gait. Field-Fote and Tepavac derived a measure based on the consistency of cyclograms over multiple cycles [52], but there is some dispute as to whether consistency is a direct indicator of greater coordination [53]

Planar covariance measures that measure the variability of body segment angles against the global vertical have also been presented as a measure of central coordination [54] while some argue that it is more affected by the passive coupling between limb segments due to the dynamics of gait [55].

D. Phase Measurement

Continuous Relative Phase (CRP) is proposed as a method of measuring coordination because limb movement during gait is almost sinusoidal, and it can distinguish between people suffering from stroke and unaffected individuals [56]. However, CRP has not always been able to track differences amongst people that simpler measures such as gait speed has [57], and it has been suggested that it is sensitive to the normalization technique used [58]. Discrete Relative Phase (DRP), where the timings of specific events such as heel strike is tracked, has been suggested as an alternative as it does not require normalization [58]. Stephenson et al., however, found no differences between healthy and post-stroke gait using DRP [59]. Nevertheless, DRP has been adapted into the Phase Coordination Index (PCI) [60] that does not seem to suffer from some of the same problems as it measures both accuracy and consistency.

All of the previous measures depend on one primary time period for gait. However, hemiparetic individuals may have different frequencies on the affected and unaffected sides. Comparing the power of these two frequencies using spectral analysis can lead to some insight into gait rehabilitation [61]. So far, it has only been used once the gait recording is complete and not actively using a method like FFT. PCA has also been used to characterize gait variation [62], but the results are not intuitive, making it hard to confirm what is being measured.

E. Balance Measures

Since a common result of imperfect gait is a reduction in the ability of the individual to balance themselves, there exists a variety of balance measures that seek to evaluate the capabilities of an individual. Sibley et al. have compiled a list of the different balance measures that are proposed and evaluate how many different aspects of balance they test [63]. The BESTest [64] was the only measure that evaluated all 9 components of balance that the authors outlined. Balance tests are mostly a clinician's tool, however, so while many authors report results of different balance tests post-intervention, they are not well suited to actively monitoring the progress of a person while using the system.

F. Cost Function Criterion

Cost function criteria are naturally suited for use with robotic systems and especially learning systems. While there is little consistency in the use of optimization criterion at the moment, Veerkamp et al. compare some of the available cost functions on a generic 18 Hill muscle musculoskeletal model to determine which individual or combination of the functions best predicts healthy human gait [65]. The physiological parameters that were considered and the cost functions that were associated with them are listed:

- Cost of Transport [66]: Calculated using the muscle metabolic model of Umberger et al [67]

$$CoT = \frac{1}{distance * mass} * \int_0^{t_{end}} \left[\sum_{m=1}^{18} \dot{E}_m(t) \right] dt$$

- Muscle Fatigue [68]: Characterized by muscle activation squared

$$MusAct = \frac{1}{distance} * \int_0^{t_{end}} \left[\sum_{m=1}^{18} activation_m(t)^2 \right] dt$$

- Head stability [69]: Characterized by the acceleration of the head

$$HeadStab = \frac{1}{distance} * \int_0^{t_{end}} \left[|a_x(t)| + |a_y(t)| \right] dt$$

- Foot Ground impact [70]: Characterized as the derivative of the GRF (yank)

$$FGIImpact = \frac{1}{distance} * \int_0^{t_{end}} \left[\left| \frac{dGRF_{x,left}(t)}{dt} \right| + \left| \frac{dGRF_{y,left}(t)}{dt} \right| + \left| \frac{dGRF_{x,right}(t)}{dt} \right| + \left| \frac{dGRF_{y,right}(t)}{dt} \right| \right] dt$$

- Knee Extension [71]: A penalty is added when knee limit torque is reached

$$KneeExt = \frac{1}{distance} * \int_0^{t_{end}} \left[F_{limit,left} + F_{limit,right} \right] dt$$

Parameter	Best performing function	R^2	RMSE
Kinematics	Cost of Transport	0.80	1.54
Joint Powers	Muscle Activation (RMSE) Foot Ground Impact (R^2)	0.46	3.66
Ground Reaction Forces	Head Stability	0.92	3.22
Joint Moments	Head Stability	0.68	2.48

TABLE III: Performance of the weighted optimal cost function along different metrics [65]

The simulations indicate that CoT was best for predicting kinematics, MusAct was best for predicting joint powers, and HeadStab was best for predicting GRFs. CoT optimization predicted the fastest gait, while MusAct predicted the slowest. The complete results are shown in Table III. Combining all parameters, however, FGIImpact had the lowest R^2 and the closest walking speed. The authors finally present a weighted sum of all five cost functions that provided the closest results to the experimental data. The choice of cost function for tracking the performance of a particular system may come down to what sensory instrumentation is available to the technician.

It is unclear how the accuracy of any of these gait characterization methods would be affected by moving a person to an underwater environment since the underwater gait of the individual is significantly different from their on-land gait. Furthermore, using energy-based methods requires further instrumentation to measure forces, which is harder to install underwater. In this situation, it is useful to consider how each metric would translate between on-land and underwater gait. Since one of the primary challenges involved in adjusting gait to the aquatic environment is being able to balance oneself, balance metrics such as head stability could be an important metric to consider. Also, coordination-based metrics such as phase measurement should be transferred to on-land situations. Other measurements could be used in a pre- and post-intervention comparison, but this limits the ability to monitor and tune the intervention while it is in action. The different methods are summarized in Table IV

VI. Design Considerations

To design underwater gait assistive robots, it is important to choose components and approaches that maximize the benefits of hydrotherapy while overcoming the challenges associated with the environment. Since a wide variety of gait assistive devices have been used to improve or support gait on land, it would be reasonable to survey the methods used for those that may translate to underwater use. The degree to which the robot influences the combined gait of the Human-Robot system ranges from artificial gait in case of complete paraplegia [72] to small supportive torques delivered at key moments in gait [73]. Correspondingly, different devices deliver torques to different combinations of joints. Also, even if a particular system leaves a specific joint unactuated, it may still augment it with passive devices. Yan et al. have studied the popularity of the different modalities that are utilized to support human gait [74], noting that while multijoint orthoses are by far the most popular systems, the most amount of user validation is present for ankle orthoses.

Gait Measure	Data Required	Evaluation method	Suitability for Underwater gait Robots
Clinical Measures	Physical Observation	Clinician expertise	Inappropriate for development of new devices as clinicians need to be present
Biomechanical parameters	Kinematics, Force measurements	Dynamic models	Useful for measuring overall efficacy
Spatial measures	Kinematics	Statistical measures	Questionable efficacy
Phase Measurements	Kinematics	Kinematic Models	Questionable efficacy
Balance Measures	Physical Observation	Clinician expertise	Requires clinician to be present
Cost Function Criterion	Kinematics, Force measurements	Dynamic models	Useful for development, but based on models, not actual human trials

TABLE IV: Summary of gait characterization methods and their suitability for underwater gait assistance device development

The different aspects of the development of gait assistive devices that were focused on were the actuators used, the integrated sensors, the different control strategies that were used, and how the system was modeled. In particular, the focus was finding what approaches would work well in underwater environments. Similar reviews have been performed for specific types of devices [75] or underwater exoskeletons without focusing on gait rehabilitation [76].

A. Actuators

a) Motorized actuators: By far, the most popular method of robotic actuation used in these papers was motors. This is not surprising because of the range of motors available, which cater to different use cases, and the supporting infrastructure surrounding them regarding drivers and control hardware and software. The predominant implementation was to attach servo motors that are mechanically parallel to the primary axis of the joints of a person [77], [83]–[85]. This considerably simplifies the modeling of the system.

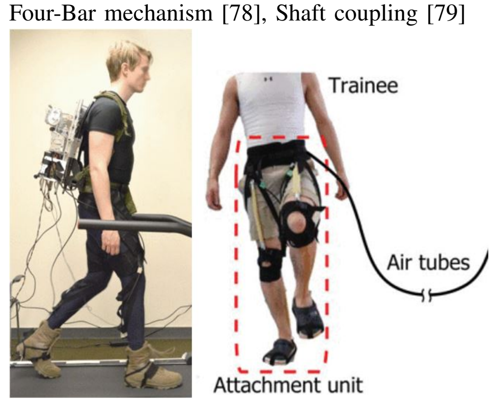
One of the issues with this system is that it requires motors to be installed on the distal areas of the user to support knee or ankle movement. This may produce an inconvenient burden on the robot or the wearer, especially underwater. Ikehara et al. work around this issue by mounting the motors on the proximal parts of the body and then transmitting the torque they generate using flexible shafts [79]. Kong and Jeon take this methodology further by relocating the motors from the body entirely, instead mounting them on a trolley that moves with a person [86]. The forces, in this case, are transmitted using a cable and pulley system. Since underwater walking is usually performed on a treadmill, this may be possible to adopt.

Motor bulk is not the only reason designers avoid implementing rotary actuators. Some researchers explore whether or not the dynamics of linear actuators are more suited to specific kinds of gait intervention [87]–[89]. Instead of converting the motion of the motor into a linear actuator, Winfree et al. developed a four-bar linkage-based actuator for their system [78]. Notably, this device also places the motors on a separate cart.

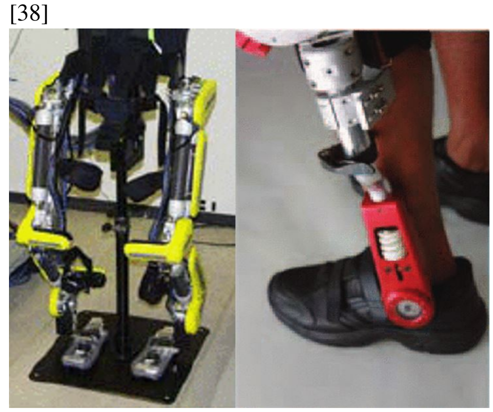
Most of these devices model the hip joint as a single-degree-of-freedom joint. However, Yu et al. developed a hip prosthesis modeled as a spherical joint, using three motors placed kinematically parallel to the directions of hip rotation [90].

b) Soft Actuators: Significant effort has gone into developing soft robotic actuators for HRI systems. The benefits of soft actuators lie in their ability to conform to complex human

(a) Motorized Actuators: Direct Alignment [77], Four-Bar mechanism [78], Shaft coupling [79]



(b) Soft Actuators: Cable driven [80], Pneumatic [38]



(c) Hybrid Actuators: Hybrid Motorized and Pneumatic Drive [81], Series Elastic Actuators [82]

Fig. 4: Examples of actuator mechanisms and implementation methods that have been used for gait assistance robotics

body geometry and the natural limitations that exist on the amount of force they can exert on the wearer, which may lead to a safer system [91]. A range of artificial muscles have been developed to serve as robot actuators [92]. Of these, pneumatic systems are the only ones that appear to have been used so far as they have the combination of power and activation latency that is suitable for such applications [93]. Miyazaki et al., for example, present a pneumatic artificial muscle-based exoskeleton that can be used both on land and underwater [38]. Varma et al. use a Bowden cable to transmit force from a cylinder mounted to the back to the leg [94]. Artificial muscles appear to be more popular for single DoF robots [95]–[97]

Artificial muscles are not the only way in which pneumatic systems can be used to support gait. In fact, a greater number of researchers have used pneumatic bladders or cylinders to exert compressive forces at joints than tensile forces as in artificial muscles [73], [98], [99]. Another approach is using cable-driven systems [80].

c) Hybrid systems: Several implementations attempt to combine the simplicity of motorized actuators with the benefits of soft actuators. One simple method is to add passive impedances to joints that may not require active support and attach motors to other joints that do require greater control [100]. This is similar to the effects noted in Section IV. One device that has become popular in recent times that combines motors and passive impedance into one unit is the Series elastic actuator (SEA). Many robotic exoskeletons have begun to take advantage of these devices in their design [42], [72], [82] as they allow for accurate force measurement and control [101]. There are also more novel implementations, such as Hyon et al., who used a combination of pneumatic and motorized actuators [81].

The wide availability of waterproof motors and the ease with which the electronics of pneumatic systems can be moved away from the actuator means that both of these approaches could work well underwater. The relative lack of underwater gait robots is evidenced by the lack of actuation mechanisms specifically leveraging underwater dynamics such as buoyancy or drag modulation. This will be discussed in more detail in Section VIII. Some examples of the actuation methods discussed are shown in Fig. 4

B. Sensors

One of the advantages of robotic devices for gait training is that they can incorporate a wide array of sensors that provide accurate and on-demand information about the performance of the system. This makes it easier for the operator and the clinician to evaluate a person's progress and modify the parameters of the device if they see fit. There is a huge variety of sensors available to designers that can provide different kinds of information. A few of them are presented below.

1) Motion Sensors: The gold standard in motion sensors is optical Motion Capture systems, especially ones that utilize active markers [102]. These provide the most accurate location data, and multiple commercial systems are available now. The main disadvantages of these systems are their bulk and computational inefficiency. This may be why they are not widely used as the active sensors for a robot's control system but are instead used as the ground truth for other sensory devices [38]. Underwater treadmills produce an additional challenge for these systems as half the user's body is underwater while the other half is above the surface, thus requiring two calibrated camera systems to track the whole body. Some commercial solutions to this have been developed [103].

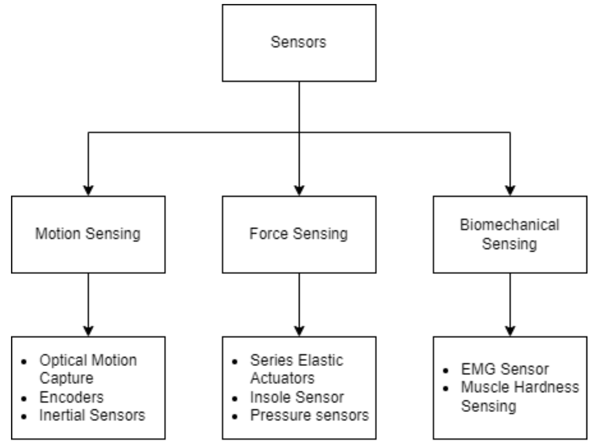


Fig. 5: Illustration of different sensing mechanisms

The most common method that gait rehabilitation robots use to track motion is to compute the forward kinematics of the system using data recorded from rotary encoders attached directly to the motors. This is particularly common for multiple degrees of freedom orthoses as they have knowledge of the configuration of multiple joints in the lower body [72], [77], [79].

Acceleration sensors can also be used to estimate the motion information of systems [42], [77], especially with the compactness of present-day IMUs [104]. However, using these sensors for determining position can lead to issues with ”drifting” though methods for correcting that have been proposed [105].

2) Pressure sensors: Systems that use pneumatic actuators need to be able to accurately monitor the pressure in the valves to estimate the amount of force that is being exerted on a person [81], [98]. However, Miyazaki et al. have proposed that the back pressure generated in artificial muscles when a person moves can be used to estimate the initiation of a new gait phase [38].

3) Force Sensors: Systems that use force-based control require force feedback to operate correctly [83]. As mentioned before, SEAs provide a high degree of accuracy in force measurement. This is particularly important when using control strategies like impedance control [84]. Another kind of force sensor that is commonly used is an insole sensor. These are useful for estimating when heel strike takes place for robots that rely on some form of gait phase identification [77], [79], [83], [106].

4) Biomechanical sensors: Direct measurement of signals generated directly by the human body may allow for more natural interfacing between humans and robots.

a) EMG sensors: EMG sensors are used for two primary purposes: sensing the intent of the wearer to perform specific actions and activate specific muscles or to evaluate the effect

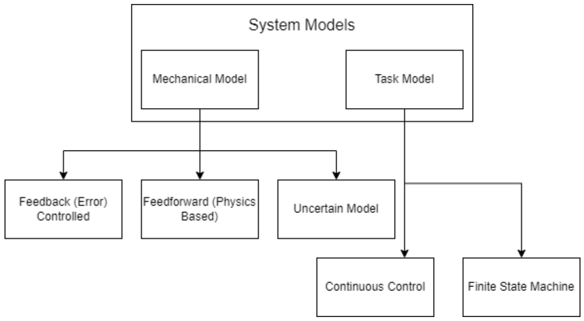


Fig. 6: Flow chart of system models with examples

of the system on the muscle activity of a person. Robots that use EMG signals [89], [107], [108] to determine the timing or degree of actuation or both leverage the electro-mechanical delay between muscle excitation and force generation [109] to provide torque at the correct time. The use of reduction in EMG excitation as a positive indicator of the robot efficacy is based on the idea that the user is required to exert less muscle force to carry out movement [42], [110]. However, there are questions about whether or not reducing the exertion of the user is beneficial for gait rehabilitation in the long term [21]. A method that is gaining popularity is to use muscle synergy to monitor gait [111].

b) Stiffness sensors: Another way in which robots sense the intent of the user is by measuring an increase in muscle hardness. Because the stiffness of the muscle increases as it is activated [112], a robot can use this information to coordinate activities. Various devices have been used to sense muscle stiffness [73], [98] but Kim et al. have extensively used piezoelectric sensors [97], [113] for multiple orthoses. Strain gauges can also be used to monitor the movements at the joints [114].

Any or all of these sensors could be incorporated into underwater applications, although some, such as IMUs, could require recalibration. The choice of sensors would likely be determined by the gait characterization method. It is also possible to combine multiple sensing modalities to gather more information using sensor fusion [115]. The different sensing modalities are summarized in Fig. 5.

C. System Models

To be able to accurately and effectively control a system, it is important to be able to model it. For gait rehabilitation robots, this problem is made much more difficult due to the inclusion of the dynamics of a human within the system. The human body is an extremely complex mechanical system with multiple degrees of freedom, and the humans themselves act as independent agents within the system, exerting their influence on the combined dynamics. In underwater environments, this problem is further complicated by the fluid dynamics of the water. While the effect of air can be ignored in most robotic applications, the viscous and inertial effects of water are too significant for similar treatment. The various methods of accounting for these challenges that have been used so far are briefly presented.

1) Mechanical Model: To derive the kinematics and dynamics of the system, it is necessary to first have a mechanical model of the system. One of the factors that influence how the system is modeled is the control scheme. Systems that rely mostly on feedback control often use simpler models as they only need to estimate the error between their desired configuration and the present configuration and produce appropriate torques to reduce it [72], [77], [100]. On the other hand, feedforward-controlled devices require higher fidelity models to correctly estimate the amount of force that would be required to execute a particular task [83], [88], [108].

a) Feedback (Error controlled) systems: In general, these systems seek to recreate a previously decided upon gait trajectory as in the case of the IHMC robot [72] or Mina [82]. Since these devices are primarily concerned about the position and velocities of the system, they only need to model the kinematics accurately.

b) Feedforward (Physics Based) systems: These devices are more often focused on generating appropriate amounts of torque at appropriate times. The range of complexity of the model varies greatly. Some systems simply increase or decrease torque based on some previously decided upon sensor reading [98], [108]. Others model the complete dynamics of the combined human-machine system to be able to use the interaction forces between the two to generate appropriate responses [116], [117].

c) Uncertain models: Instead of attempting to derive a deterministic model of the system, Yang et al. assume that some uncertainty will exist and use an RBF neural network to model this uncertainty [84]. Such models that leverage machine learning may be better suited to devices that operate in uncertain conditions like underwater.

2) Task modelling: In addition to the mechanical model of the system, the activity of the gait itself must be modeled. In this respect, there are two main categories: finite-state devices and continuous-controlled devices.

a) Continuous Control: These devices use a consistent control strategy irrespective of which phase of gait the operator is currently in [72], [79], [82]. Many of these robots are error-controlled and, therefore, do not need explicit knowledge of what specific task a person is about to perform and do not need to modify the control scheme to suit that specific task.

b) Finite state machines: Many of the model-based robots use different models depending on which phase a person is currently in, with the most common differentiation being between stance and swing phase [42], [77], [100]. This is due to the dynamics of the system being fundamentally different if the system is in contact with the ground. Different devices use different methods to identify when a phase change occurs. As mentioned, foot sole sensors are a common method [83]. Suzuki et al. present two other identification methods, one based on which foot is carrying a greater load and one based on the tilting angle of the torso [77].

The different aspects and approaches for system modeling are shown in Fig. 6. The approach for adapting each of these methods to underwater environments would likely be different. Feedback-based approaches could automatically overcome the disturbances caused by the change in environment, but feedforward systems will likely need to account for the effects somehow. Accurately modeling fluid forces requires complex CFD simulations, which don't work well with real-time applications. Thus, a simplified model will likely have to be developed to do this.

D. Control strategies

Control strategies essentially determine the relationship between the input signals received by the robot and the output signals that it generates. Naturally, the kind of control architecture that a robot uses is heavily dependent on the kinds of sensors and actuators that it uses. A very wide range of control strategies is used for gait rehabilitation robots; hence, they are summarized here based on the authors' approach. Miguel-Fernandez et al. have reviewed the different control strategies and their popularity [118], concluding that most designs use trajectory tracking using gait phase identification, and only a few use adaptive approaches. A combination of trajectory tracking and compliance was shown to have the highest demonstrated efficacy, a strong motivation for underwater compliant actuation.

1) Periodicity based controllers: This class of controllers heavily leverages the cyclical nature of gait. Especially when an individual is undergoing gait training, the tasks involved in the process are repetitive and predictable. Most of the controllers described here are kinematic controllers and are based on an ideal "healthy gait" that is predetermined. In the case of underwater walking, this presents an additional challenge in deciding what a "healthy" underwater gait is. These devices can be categorized based on how much they adjust this ideal gait for each person when implementing their controllers.

a) Pure torque or position controlled: These controllers do not modify the target trajectory between people. These are most often multiple degrees of freedom devices that use PID controllers to execute the same pre-loaded trajectories to the greatest extent possible, usually with some safety precautions to ensure that they do not overburden the wearer [72], [82]. These devices are most often position controlled [72], [82] though some are also torque controlled [108], [111], [119]. They often use intent mapping to decide when to move from one desired configuration to another [108].

b) Dynamic Time warping: While these controllers also use a predefined ideal gait, they use different strategies to scale the trajectories to individuals. They may be scaled linearly based on the walking speed of each wearer [77], or individual phases may be scaled based on certain events being triggered manually [42].

c) Energy minimization: Sanz-Merodio et al. use an energy optimization program based on the physical specifications of a person to derive an ideal gait that is custom-made for each individual [100]. As noted previously, energy minimization may not be the best approach to achieving a healthy human gait.

d) Hybrid system: Miyazaki et al. are noted separately here because while they do use feedback from the user to initiate actuation, the sensory windows only open at key periods which are predetermined [38]. Thus, their system is also somewhat dependent on a known cadence. Another approach is to use the kinematics of the healthy leg to determine the goal for the assisted leg [120].

The concern with these systems is that if they were implemented in underwater environments, they would likely overpower the dynamics of the environment, rendering the change in the environment largely irrelevant. While changes to the cycle times and programmed kinematics could be made to account for the underwater forces, it would substantially reduce their influence unless the forces exerted by the system were modulated sufficiently.

2) User-initiated control systems: Instead of having prior knowledge about the gait that will be executed by the human-robot system, these controllers use sensors attached to the human to determine when and to what extent the actuators should be activated. Since the forces that are generated are dependent on what the user does, these robots are almost always force-controlled. The movement that is generated during operation is a result of the forces exerted by the wearer and the robot, not pre-planned.

a) Impedance control: These devices are the closest to the previous category of robots in that they also have a desired configuration that they are programmed with. However, instead of imposing that configuration on the wearer, they generate forces that increase the further the wearer strays from the configuration [42], [84]. The wearer is, therefore, physically incentivized to recreate the desired gait. Depending on the perspective of the controller, this may also take the form of admittance control, where the user is only allowed a certain healthy range of movement [121]

b) Adaptive Control: Adaptive oscillators were developed by Righetti et al. [122]. The implementation of these controllers is based on the periodicity of the gait cycle [78], [123]–[125]. Unlike fixed frequency controllers, these robots actively adjust their period based on new information. This allows the device to not only optimize itself for each user but also change its behavior as the user's gait changes over time [125].

c) Fuzzy Control: Fuzzy controllers are used to create an input-output relationship in the continuous domain from rules written in a discrete domain or based on mathematical formulations [126]. Implementing these systems requires an "expert system" to generate the rules based on prior knowledge of the process. In the case of gait rehabilitation robots, the person is treated as the expert system. Biological parameters such as EMG [110] or muscle stiffness [86] are used to determine supportive torques. While these robots can help people with muscle weakness, it is unclear whether they would help people rebuild muscle strength, as this has not been investigated in the papers.

d) Sensitivity Amplification: In some ways, sensitivity amplification is the opposite of error control as, instead of minimizing a disturbance using a negative feedback loop, it attempts to conform to the disturbance using a positive feedback loop [83]. Robots with these control architectures are designed to increase the load carrying capacity of the operator [83], [127], rather than focus on rehabilitation, and are hence not the focus of this paper.

The adaptability of these controllers may make them better suited to exploiting, rather than overpowering, the dynamics of an underwater environment. If an appropriate controller objective can be determined, as discussed in Section V, a system could use feedback from the user and the sensed or modeled response from the environment to modulate the forces beneficially.

3) Momentary activation: Some robots are designed to provide impulsive forces at key moments in gait like toe lift instead of continuously controlling their output [73], [80]. This may be an appropriate rehabilitation method for some people if the assistive force can be tuned appropriately. However, because of the large damping of the underwater environment, impulsive forces would likely have a reduced influence.

VII. Supplemental Methods

Some methods are used in conjunction with exercise therapy during gait rehabilitation. The efficacy of these techniques, when coupled with hydrotherapy, would require extensive experimentation to be validated. However, the change in dynamics in the underwater environment may pair with an approach better than the more regular environment of overground gait training.

A. Functional Electrical Stimulation

One method of increasing a person's muscle activation is to augment their auto-generated impulses with external electrical impulses. This is still a relatively novel approach to gait rehabilitation. Like many other kinds of interventions, FES is more effective soon after the victim suffers the stroke [128]. In such cases, statistically significant benefits have been reported in favor of such methods [128], [129] . In the case of partial SCI people, FES treatment had positive effects that persisted even after the system was disconnected [130]. Lam et al. analyze the effects of combining FES with other treatment methods, such as BWS and orthoses [13].

B. Brain Computer Interfaces (BCI)

BCI systems build on Motor Imagery Practice by providing data on the cortical activation of a person when they are involved in the treatment. While many methods of measuring brain activity, Belda-Lois et al. suggest that electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS) are the most promising because they are minimally invasive and relatively inexpensive. Daly et al. showed parallel improvements in motor function and changes in post-stroke EEG [41]. The use of fNIRS in gait analysis is less common, though Miyai et al. have argued for the involvement of the premotor cortex in gait restoration [131].

C. BioFeedback

Biofeedback methods record a person's gait parameters and then replay them using imagery or sound during training as a reinforcement strategy. The most common parameters are kinematic [132] although parameters such as EMG signals a person generates during their movement are also used [133]. This method has shown some positive results, but its efficacy has not been fully demonstrated due to the lack of long-term studies, including control groups [132]. Integrating these methods with hydrotherapy, if desired, should not pose significant challenges.

VIII. Discussion

From the overview of the different kinds of gait disorders, it is clear that they pose different challenges. Depending on the particular issues a person faces, the clinician may recommend slightly different forms of gait rehabilitation training. For issues caused by a weakness in the muscles like waddling gait or steppage gait, the gait assistance device is likely to prove most useful if it only provides the amount of force necessary to keep a person from losing balance or otherwise not being able to practice walking. This would give a person the ability to strengthen their muscles without risking injury. For disabilities caused by the inability to coordinate muscle activity, the device may have to operate as a guide, incentivizing them to perform certain "healthy" motions using some form of force feedback. Not all gait conditions lend themselves to this form of treatment, as already discussed [4]. Also, this discussion is focused on gait rehabilitation. Robots that are designed to be a permanent aid for people for whom it is not possible to completely reacquire healthy gait have different objectives and requirements and are incompatible with hydrotherapy. Nevertheless, some of the systems used on them may still be relevant.

In section IV, the current literature regarding the benefits of hydrotherapy was presented. Walking underwater has the dual effects of making some tasks easier while also demanding higher energy outputs from a person [3]. Designing effective underwater gait rehabilitation devices will likely involve modulating and channeling these effects. It is clear that simply by using weights or buoyancy cuffs, one can change the effects of the water [33]. Well-designed active devices may be able to have finer control over these forces. There are challenges associated with designing devices that work effectively underwater, which may explain the small number of such platforms, but the development of other underwater robots, such as AUVs, shows that possible solutions also exist.

In Section V, different methods of characterizing gait performance were presented. Quantifiable metrics such as the ones tested by Veerkamp et al. [65] will be of particular appeal to researchers as they remove the need for a trained specialist to be present at all phases of development. Since the performance of a gait assistance robot is eventually tied to the performance of the person using it, it is unclear whether there is any systematic way to analyze the effectiveness of a gait rehabilitation platform without testing it on the people they are being designed for. Many researchers have carried out tests on healthy people in an attempt to understand the effect of their platform [38], [40], but whether or not the effects would carry over to people is unknown. Almost all gait rehabilitation robots suffer from a lack of long-term, high-quality studies [118]. As noted, these issues are compounded in underwater environments, as the idea of a "healthy underwater gait" is not as clear as it is for on-land walking. It may, therefore, be necessary to periodically characterize the gait of the participating individual out of the water to track their progress.

When it comes to the actual design of the robot, the considerations include the choice of actuators, sensors, and control systems. When choosing an actuation mechanism for their device, a researcher must balance the amount of force they can generate, the control they have over their system, and the risk of causing harm to a person. One of the major benefits of underwater environments is their compliance and damping, so if the environment could be included in the force transmission chain, it may provide a way to leverage this benefit. However, this would require the purposeful design of the actuation method. For on-land devices, motors are still the actuator of choice because they are ubiquitous and predictable in their behavior. Safety in motorized systems is largely based on the ability to monitor and intervene when the system may behave improperly. On the other hand, alternate actuators like pneumatic systems may, as soft actuators, reduce the possible harm to a person in case of a malfunction, even though their complex dynamics make them more unpredictable [38], [39]. It is possible that with the development and study of new actuators, these relationships will change.

For gait rehabilitation, robot sensors serve two major purposes: providing information about the robot and providing information about a person. While the former is necessary for robust device control, the latter may have different uses depending on the control scheme. For robots that simply perform the same repetitive tasks, it may serve to benchmark the effectiveness of the device. However, for devices with deeper integration between the human and the robot, these sensors may form a vital input to the control architecture [89], [98], [107], [113]. This leads into the question of what control system is most appropriate for these devices. The overview of gait rehabilitation strategies and their effectiveness indicates that a person must maintain some degree of autonomy during the process. Therefore, it is unlikely that robots that make all decisions about the movement on a person's behalf will be useful in the long term. This also questions the common use of reduction in EMG signal strength as an indication of good performance [37] as increased voluntary motion may be the objective of gait training. To utilize the effects of water in the gait training process, it may be necessary to add sensors that monitor the conditions of the water or the components that interact with it and then consider that in the control structure.

Most gait rehabilitation systems are based on the idea of supporting a person while they regain gait competence. The burden is on a person to solve the difficulties they face themselves, with the treatment systems either protecting them from injury, providing them information about what aspects of their walking performance they need to focus on and the progress they are making towards recovery, or enabling them to practice gait in a repeatable, controlled fashion. For this reason, many of these systems can be used in conjunction with each other. It is not unforeseeable for a person to combine FES with a gait assistance robot while walking on an underwater treadmill and tracking their progress using a BCI. Therefore, researchers designing such robots may seek to explore the ability to integrate combinations of these different technologies into their platforms.

Research Opportunities

The use of underwater actuation mechanisms for gait rehabilitation robotics is severely limited. Other underwater devices use a wide variety of different principles such as buoyancy modulation [134], jet propulsion [135], hydrofoil-based control [136], etc., which may be useful in expanding the range of control architectures that can be applied towards gait training. The authors have explored the application of these methods to gait modification applications in the past [137], [138]. Some of the challenges associated with using these forces are the complex dynamics and that the forces are aligned to the ground reference frame and do not change orientation with the person as they move. Hydrotherapy can passively implement some principles, such as body weight support and passive impedance, that overground systems require careful design to achieve. Leveraging these effects while exploring the available range of human-robot interaction schemes may lead to the development of devices that have distinct advantages over ground systems.

There is also a need to model the fluid dynamics surrounding underwater gait, both to gain a greater understanding of the effect of underwater walking on the human body and also to create control systems that can account for the differences. The former likely requires more complex and accurate models to gain accurate insight. Integrating the effect of submersion in biomechanical models could prove useful in understanding the potential benefits of hydrotherapy in a quantifiable way. However, when designing robots, it is likely necessary to create simplified models that do not slow down the controller and incorporate error correction to overcome inaccuracies.

Conclusion

Gait training is a viable approach for treating gait impairments caused by various physiological ailments. While many approaches have been used to develop robots that aid such procedures on land, there is a shortage of platforms that operate underwater. There are observable benefits to carrying out gait training underwater, which would indicate that research into the design of such robots may lead to long-term benefits for many individuals suffering from such ailments.

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