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Review

Ankle Injury Rehabilitation Robot (AIRR): Review of Strengths and Opportunities Based on a SWOT (Strengths, Weaknesses, Opportunities, Threats) Analysis

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Abstract: Generally, severity, any additional damage to the joint surface, and the optimal rehabilitation influence the recovery of an ankle injury. Optimal rehabilitation is the only approach for a human to heal as soon as possible. Ankle injury rehabilitation robots (AIRRs) are designed to fulfil the ideal rehabilitation by providing the required accuracy, consistency, and repeatability, compared to conventional rehabilitation methods. This review is to explore the performance of the existing AIRR using a SWOT analysis with a focus on the strengths and opportunities of an AIRR. Sources from journals and conference papers are selected for review after several screenings, according to the search conditions set by the authors. The results have shown a large group of AIRRs could accomplish all basic ankle motions and select parallel mechanisms to drive the foot platform. Most AIRRs provides crucial feedback sensors, such as position, torque, and angle. These factors determine the accuracy of the foot platform. Both the electrical/pneumatic actuation and wearable/platform-based AIRRs have their purpose for rehabilitation and must be considered as equal contributions to ankle injury rehabilitation research using robots. Opportunities to provide innovation to the already established AIRR research still exist in the ability to accommodate complex motion ankle rehabilitation exercises and to establish teaching and playback into the rehabilitation procedures for AIRRs. In general, the existing strengths of AIRRs provide advantages to patients where they can enhance the rehabilitation procedures while opportunities and knowledge gaps for AIRR research are still open to improvement.

Keywords: ankle rehabilitation; ankle injury; biomedical; automated rehabilitation; rehabilitation robotics; rubric assessment; review

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1. Introduction

The ankle (talocrural) is one of the most exceptional human joints where the functional stability and the mobility of the joints are compatible. This human joint feature is unique, compared to other human joints, such as the elbow and saddle joint, where its function is limited to either functional mobility or functional stability [1]. These unique features of the ankle joint have allowed people to perform physical motions, such as jumping, walking, running, etc. [2]. However, the ankle joint is prone to injury, attributable to domestic-related accidents or sports-related accidents [3]. There are three classifications of ankle injury:

ankle strain, ankle fracture, and ankle sprain. An ankle sprain is the most common type of ankle injury, especially in sports-related or domestically related activities [3–5].

An ankle sprain is inclined to reoccur for athletes who have experienced an ankle sprain for the first time, based on the medical history survey conducted by Lamb et al. [6], who suggested in their study that an ankle injury has a higher chance to reoccur if the injured ankle is not completely recovered, due to the absence of appropriate treatment. If the immovable injured ankle is prolonged without proper rehabilitation, the ROM of the ankle joint can also be diminished and there is a higher chance of a secondary injury to the lower limb chain [7]. Additionally, the New South Wales Institute of Sports Medicine has advised that an ankle injury can lead to instability and to long terms disability, if a high number of symptoms, following the ankle inversion injury, is sustained. These symptoms can be persistent if the recuperation of the ankle injury is not being appropriately and regularly managed [8].

To maintain a regular recovery, it is ideal that patients undertake a home-based rehabilitation, instead of going to the hospital or a rehabilitation clinic. This is important so that the patients can recover naturally and can increase the speed of their rehabilitation by themselves, thus minimizing hospital visits. Conventionally, home-based rehabilitation can be achieved with the application of elastic bands and wobble boards. This approach can be accomplished effectively in an active rehabilitation instead of in a passive rehabilitation. Commonly, a passive rehabilitation necessitates two persons (therapist and patient) for participation and the rehabilitation procedures are tedious and inconsistent [9]. This causes a decision-making inaccuracy by the doctors or therapists when treating the patients. If more than one patient requires rehabilitation at one time and at the same rehabilitation center, this situation can be a burden to the therapist, both physically and mentally, due to the extra workload from the rehabilitation that can potentially be reduced with the application of robots or machines.

Moreover, ankle rehabilitation can be enhanced by presenting a robot or an automated devices to take over some of the rehabilitation procedures, as a form of support to the existing rehabilitation procedures. The robots are not intended to replace all human-based rehabilitation activities. Until now, machines are still lacking in human touch, especially in dealing with pain. However, this is plausible if the ankle anatomy and robot anatomy are well-suited to each other. There is a study, whereby existing robots or devices have effectively restored the lost function of an individual’s ankle, such as robotic workstations, orthosis, robotic wheelchairs, and feeding devices [10]. These show that there are some accomplishments of matching the robot anatomy with the ankle anatomy in the past robot-assisted ankle rehabilitations.

Robots have a productive potential, and less supervision is required in serving the patients. The ability to maintain consistency and repetition is also one of the greatest benefits of rehabilitation robots [11]. Studies suggested that an ankle injury rehabilitation robot or AIRR has the potential to provide diagnostic and therapy customization. An AIRR is also capable of maintaining its record performance during the rehabilitation and is capable of monitoring and measuring the rehabilitation progress of the patients [2,9,10,12–14]. Furthermore, an AIRR provides multi-functionality by merging functions that are accessible in current ankle rehabilitation training, such as balance function training (wobble board) and ankle strength training (elastic bands) [11,12].

Previous AIRR review publications have been published by Dong et al. (2021), who focused on a parallel type AIRR., Jiang et al. (2018) focused on the anatomy review of AIRRs, Shi et al. (2019) focused on a wearable type AIRR, Miao et al. (2017) focused on a platform-based type of AIRR, Perez et al. (2019) focused on both wearable and platform-based types of AIRRs, Khalid et al. (2015) focused on the mechanical design of a type of AIRR, Jiang et al. (2019) covers all of the reviews of AIRRs, based on the structure type, drive type, training mode, and application situation [15–21].

Based on the previous reviews, there is a huge opportunity, whereby reviewing AIRRs can be used to identify the significant features of the current AIRRs, in terms of strengths and opportunities, using a SWOT analysis from an engineering perspective. Additionally, this review will provide the subjective measurement for each AIRR, in terms of criteria, such as capability, portability, innovation, and scope of usage, through a SWOT (strengths, weaknesses, opportunities, and threats) analysis. The weaknesses and threats indicators from the evaluation are being ignored. Through this review, readers can identify the features of AIRRs, in terms of their advantages and the prospects of these robots to inspire improvements in the future, and to prevent the continuous improvement of rehabilitation robotics from becoming stagnant. Overall, the main aim of this review is not to discredit the AIRR review publications, but to acknowledge their achievements and to provide suggestions and improvements for future researchers to continue the established works. This review also provides additional knowledge and a new perspective to the already published AIRR reviews, based on strengths and opportunities.

2. Materials and Methods

This review provides an insight into the established AIRRs, based on the advantages and new research prospects. The databases, such as Web of Sciences, SCOPUS, IEEE Explore, SpringerLink, Sage Publications, WILEY Online Library, IOP Science, ACM DL Library, ASME Digital Collection, Emerald Insight, and Science Direct were sourced using keywords and phrases such as "ankle*" and "robot*". The relevant articles are identified and selected with full access.

2.1. Inclusion Criteria for the Review

Sources were accepted for review if the following acceptance criteria for review were met:

(1) Sources were accessible to the authors.
(2) The articles were written in the English Language.
(3) The existing AIRRs must be used to rehabilitate an ankle injury (this includes ankle sprains or ankle strains).
(4) AIRRs must be developed with physical prototypes and not concept designs and analytical prototypes.
(5) Any sources that were encompassing both the rehabilitation for an ankle disability and the rehabilitation for an ankle injury.
(6) Sources after 1990 were included in this review.

2.2. Exclusion Criteria for Review

Sources were rejected for review if the following rejection criteria for review were identified:

(1) Sources were not written in the English Language.
(2) The existing AIRRs specify the purpose of the rehabilitation are for an ankle disability only and not the rehabilitation for an ankle injury.
(3) Studies with a lack of information regarding the existing AIRRs.
(4) Studies that were still under the proposal stage.
(5) Sources before 1990 were excluded from this review.

These criteria were set in such a way because a study, based on a physical prototype can provide a lot of necessary information for the review, compared to an analytical prototype, especially for information regarding the hardware, such as sensors and actuators.

2.3. Use of the SWOT Analysis in the Review

The main aim of using a SWOT analysis is to characterize the strengths, weaknesses, opportunities, and threats, to decide the strategic position of a company [21,22]. Although a SWOT analysis is used to assess a person, place, product, or even an industry, a SWOT analysis has also often been used in the field of healthcare, compared to agriculture, according to Benzaghta et al. (2021) [22]. This study was significant as healthcare rehabilitation requires decision-making to determine the practicality of the listed options [23,24]. Therefore, in this technical review, the SWOT analysis, with the exception of weaknesses and threats indicators, is used to evaluate the research trend of AIRR developments, based on the obtainable sources presented through the technical knowledge of the reviewers. Figure 1 presents the structure of the SWOT analysis with examples of the components relating to AIRRs.

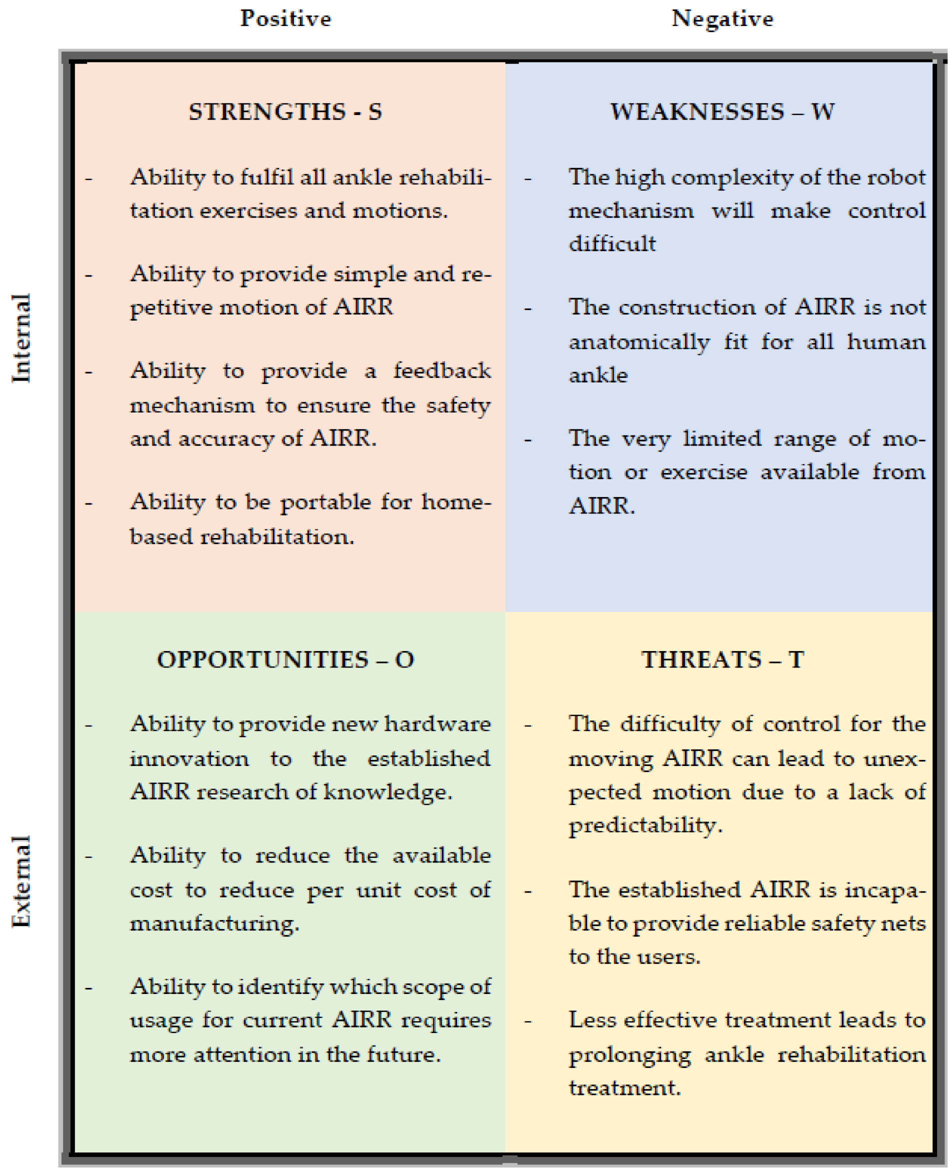

Figure 1. SWOT Analysis Diagram with examples of its components relating to AIRRs.

The main reason the negative factors from the SWOT analysis, such as weaknesses and threats, are discarded from the review is that these indicators provide a biased evaluation of the existing robot as some of the weaknesses are intentional to fulfil a specific purpose or scope of a previous project. For example, one of the researchers might opt to develop a 1 DOF (degree of freedom) AIRR only, from the start, as part of his or her research scope. However, if the weaknesses and threats criteria from the SWOT analysis are applied, his or her works would be unfairly undermined in this review. For instance, a robot that can fulfil the whole 3 DOFs (representing the whole ankle motion) is better than fulfilling only 1 DOF. Therefore, to prevent the unfair judgment on the established AIRR, only the strengths and opportunities of the existing robots are selected as the main indicators for this article, from the SWOT analysis, to highlight the accomplishment of the existing AIRRs (through strengths) and to provide inspiration to the incoming researchers to provide new knowledge and improvements to the already established AIRR research (through opportunities).

The main benefit of the SWOT analysis is that this analysis can present the internal and external factors that were beneficial for the reviewed AIRR, by looking at the established AIRR from two perspectives—present and future. Additionally, this review is not only celebrating the achievements of the previous AIRRs but also provides suggestions for new contributions and knowledge gaps that have been identified by the reviewers, which can inspire future researchers of AIRRs to create a breakthrough in the established AIRR research.

2.4. Selection Review Process

Based on the selection reviewing process in Figure 2, the sources that focused on an ankle disability and related to neurological impairments only, were excluded from the review [25–120]. Sources that contained only the analytical prototyping, analysis, design, and simulation stages were also removed [121–149]. Sources were gathered until August 2022. Based on the selection process, 27 AIRRs were selected for review. Table 1 presents a summary comparative table on ankle injury rehabilitation robots (AIRRs), according to the features of AIRRs, such as the DOF, actuation, mechanism, covered ankle motion, sensors, platform or wearable, and training mode.

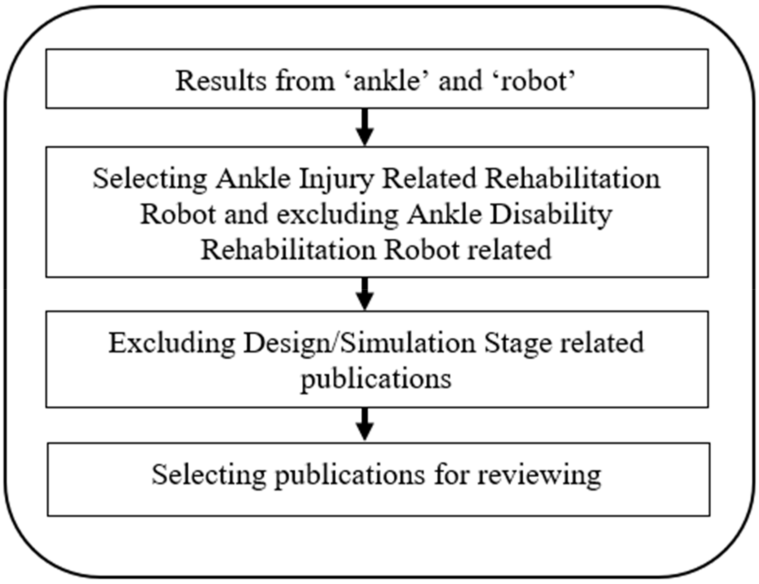

Figure 2. The flow of the selection reviewing process.

Table 1. Summary comparative table on the ankle injury rehabilitation robots (AIRRs).

No.	Ankle Injury Rehabilitation Robot AIRR	Author (Latest Year) [References]	DOF (with Type of Motion)	Actuation	Mechanism	Covered Ankle Motion	Sensors	Platform/Wearable	Training Mode
(1)	Ankle Rehabilitation Robot (ARBOT)	Saglia et.al. (2011) [11,150].	2 DOFs (2 Rotational)	Electrical	Parallel Mechanism Linear Actuation Capstan System of Pulleys	Plantarflexion Dorsiflexion Inversion Eversion	Six Axis Force/Torque Sensor Position Sensor Optical Encoder	Platform	• Patient-passive Exercises: Isometric Strengthening Exercises; • Patient-Active Exercises: Strengthening and Assistance; • Isokinetic Training.
(2)	Wearable Soft Parallel Robot	Jamwal et.al. (2020) [151–153]	3 DOFs (3 Rotational)	Pneumatic	Cable Driven Mechanism Air Muscles Parallel Mechanism	Dorsiflexion Plantarflexion Adduction Abduction Inversion Eversion	Pressure Sensor Force Sensor Linear Potentiometer	Wearable	• Passive Training; • Position and Zero-Impedance Control; • Isokinetic Training.
(3)	Rutgers Ankle	Girone et.al. (1999) [154,155]	6 DOFs (6 Rotational)	Pneumatic	Parallel Mechanism	Plantarflexion Dorsiflexion Inversion Eversion	Force Sensor Linear Potentiometers Pressure Sensor	Platform	• Passive Training; • Strengthening Exercise; • Flexibility Exercises (ROM); • Balance Exercise; • Isokinetic Training.
(4)	Reconfigurable Ankle Rehabilitation Robot	Yoon et.al. (2005) [156,157]	4 DOFs (1 Prismatic + 3 Rotational)	Pneumatic	Reconfigurable Parallel Mechanism	Plantarflexion Dorsiflexion Inversion Eversion	N/A	Platform	• Passive Training; • ROM (Range of Motion); • Strengthening; • Balance/Proprioception • Isokinetic Training.

Table 1. *Cont.*

No.	Ankle Injury Rehabilitation Robot AIRR	Author (Latest Year) [References]	DOF (with Type of Motion)	Actuation	Mechanism	Covered Ankle Motion	Sensors	Platform/Wearable	Training Mode
(5)	Three RSS/S Ankle Rehabilitation Parallel Robot	Liu et.al. (2006) [158–160]	3 DOFs 3RSS/S (1 Rotational-1 Spherical-1 Spherical)	Electrical	Parallel Mechanism	Dorsiflexion Plantarflexion Adduction Abduction Inversion Eversion	Force Sensor Rotary Encoder	Platform	• Passive Training; • Isokinetic Training.
(6)	Rotating Magnetorheological Damper for Ankle Rehabilitation Robot (R-MRF-D)	Zheng J. et.al. (2020) [161]	1 DOF (1 Rotational)	Electrical	Magnetorheological Fluid (MRF) Spring Mechanism	Dorsiflexion Plantarflexion	Torque Sensor Speed Sensor	Platform	• Passive Training; • Isokinetic Training.
(7)	SUKorpion	Satici et.al. (2009) [162,163]	2 DOFs 3UPS-RR Combination of UPS (1 Universal-1 Prismatic-Spherical) + RR (1 Rotational-1 Rotational)	Electrical	Parallel Mechanism	Plantarflexion Dorsiflexion Inversion Eversion	Rotary Encoder Motion Tracker	Wearable	• Passive Training; • Range of Motion/Strengthening Exercises; • Balance/Proprioception Exercises; • Isokinetic Training.
(8)	Three DOF Ankle Rehabilitation Robot	L.Wang et.al. (2014) [164]	3 DOFs (1 Rotational-1 Rotational-1 Rotational)	Electrical	Turbine Worm	Dorsiflexion Plantarflexion Adduction Abduction Inversion Eversion.	Rotary Encoder Accelerometer	Platform	• Passive Training; • Isokinetic Training.

Table 1. *Cont.*

No.	Ankle Injury Rehabilitation Robot AIRR	Author (Latest Year) [References]	DOF (with Type of Motion)	Actuation	Mechanism	Covered Ankle Motion	Sensors	Platform/Wearable	Training Mode
(9)	Vi-RABT (Virtually Interfaced Robotic Ankle and Balance Trainer	Farjadian et al. (2019) [165]	2 DOFs (1 Rotational-1 Rotational)	Electrical	Pulley Poly Chain Timing Belt	Plantarflexion Dorsiflexion Inversion Eversion	Angle Sensor Force Sensor Optical Encoder	Platform	• Passive Training; • Balance Training; • Isokinetic Training.
(10)	Compliant Ankle Rehabilitation Robot (CARR)	Zhang et al. (2018) [166–171]	3 DOFs (1 Rotational-1 Rotational-1 Rotational)	Pneumatic	Fluidic Muscle Parallel Mechanism	Dorsiflexion Plantarflexion Adduction Abduction Inversion Eversion	Six Axis Load Cell Magnetic Rotary Encoders Force Sensors	Wearable	• Passive Training; • Repetitive Training; • Patient-Cooperative Training; • Isokinetic Training.
(11)	Wearable Ankle Rehabilitation Robot	Zhou et al. (2016) [172]	3 DOFs (1 Rotational-1 Rotational-1 Rotational)	Electrical	Linear Actuation Parallel Mechanism	Dorsiflexion Plantarflexion Adduction Abduction Inversion Eversion	Inclinometer Sensor Limit Switch	Wearable	• Passive Training; • Repetitive Training; • Isokinetic Training.
(12)	Novel Parallel Robot for Ankle Rehabilitation	Li et al. (2020) [173–178]	3 DOFs 2 UPS/RRR Combination of UPS (1 Universal-1 Prismatic-Spherical) + RRR (1 Rotational-1 Rotational-1 Rotational)	Electrical	Parallel Mechanism	Dorsiflexion Plantarflexion Adduction Abduction Inversion Eversion	Force Sensor Torque Sensor Tension/ Pressure Sensor Angle Sensor Rotary Encoder	Platform	• Passive Training; • Passive Compliance; • Active Training; • Isokinetic Training; • Muscle strength Exercise.

Table 1. *Cont.*

No.	Ankle Injury Rehabilitation Robot AIRR	Author (Latest Year) [References]	DOF (with Type of Motion)	Actuation	Mechanism	Covered Ankle Motion	Sensors	Platform/Wearable	Training Mode
(13)	Redundant Pneumatic Muscles-Cable-Driven Ankle Rehabilitation Robot	Lu et al. (2022) [179,180]	3 DOFs (1 Rotational-1 Rotational-1 Rotational)	Pneumatic	Pneumatic Muscles Proportional Calve Regulator Parallel Mechanism Cable Driven Mechanism	Dorsiflexion Plantarflexion Adduction Abduction Inversion Eversion	Six Axis Force/Torque Sensor Magnetic Angle Sensor (X-Axis, Y-Axis, and Z-Axis) Force Sensor Displacement Sensor	Platform	• Passive Training; • Isokinetic Training.
(14)	Robot Assisted Ankle Stretching	Chen et al. (2017) [181,182]	1 DOF (1 Rotational)	Electrical	Belt Drive	Dorsiflexion Plantarflexion	Uni-Axial Torque Sensor Rotary Encoder Inclinometer Current Sensor	Wearable	• Passive Training; • Isokinetic Training; • Passive Stretching.
(15)	Redundantly Actuated Ankle Rehabilitation Robot	Ayas and Atlas (2016) [183,184]	2 DOFs (1 Rotational-1 Rotational)	Electrical	Linear Actuation Parallel Mechanism	Plantarflexion Dorsiflexion Inversion Eversion	Force Sensor	Platform	• Passive Training; • Active Training; • Isometric Exercise; • Isotonic Exercise; • Strengthening Exercise; • Isokinetic Training.

Table 1. *Cont.*

No.	Ankle Injury Rehabilitation Robot AIRR	Author (Latest Year) [References]	DOF (with Type of Motion)	Actuation	Mechanism	Covered Ankle Motion	Sensors	Platform/Wearable	Training Mode
(16)	AssistON-ankle	Erdogan et al. (2016) [185]	6 DOFs Combination of 3 UPS (1 Universal-1 Prismatic-Spherical) + 3RPS (1 Rotational-1 Prismatic-1 Spherical)	Electrical	Lockable Passive Universal Joint Modules Parallel Mechanism	Dorsiflexion Plantarflexion Adduction Abduction Inversion Eversion Supination Pronation	Force Sensor	Wearable	• Passive Training; • Balance/Proprioception Training; • Repetitive Stretching and Strengthening Exercises; • Isokinetic Training.
(17)	Three-PRS Parallel Robot	Abu Dakk et al. (2015) [186]	3 DOFs (1 Prismatic-1 Rotational-1 Spherical)	Electrical	Parallel Mechanism	Plantarflexion Dorsiflexion Inversion Eversion	Force Sensor	Platform	• Passive Training; • Plantarflexion/Dorsi flexion Exercise; • Isokinetic Training.
(18)	Pneumatic Muscles-Driven Ankle Rehabilitation Robot	Zhang et al. (2017) [187–189]	2 DOFs (1 Rotational-1 Rotational)	Pneumatic	Pneumatic Muscles Cable and Pulley Driven Mechanism Parallel Mechanism	Plantarflexion Dorsiflexion Inversion Eversion	Force Sensor Displacement Sensor	Platform	• Passive Training; • Synchronous Training; • Asynchronous training; • Isokinetic Training.
(19)	Rehabilitation Robot for Continuous Passive Motion of Foot Inversion-Eversion	Alipour and Mahjoob (2016) [190]	4 DOFs (3 activeDOFs) (1 Rotational-1 Rotational-1 Rotational)	Electrical	Gear and Pinion Transmission System	Dorsiflexion Plantarflexion Adduction Abduction Inversion Eversion	Rotary Encoder Current Sensor	Wearable	• Passive Training; • CPM or Continuous Passive Motion Training; • Isokinetic Training.

Table 1. *Cont.*

No.	Ankle Injury Rehabilitation Robot AIRR	Author (Latest Year) [References]	DOF (with Type of Motion)	Actuation	Mechanism	Covered Ankle Motion	Sensors	Platform/Wearable	Training Mode
(20)	Movable Ankle Joint Stretching Device	Sugihara et al (2019) [191]	1 DOF (1 Rotational)	Electrical	Pantograph Jack Tension Rod Structure Linear Actuation	Plantarflexion Dorsiflexion	Force Sensor Acceleration Sensor	Wearable	• Passive Training; • Isokinetic Training.
(21)	A One Degree-of Freedom Ankle Rehabilitation Platform	Doreftei et al. (2019) [192]	1 DOF (1 Spherical)	Electrical	Parallel Mechanism	Plantarflexion Dorsiflexion Inversion Eversion	N/A	Platform	• Passive Training; • Isokinetic Training.
(22)	Ankle Rehabilitation Device with Two Degrees of Freedom and Compliant Joint	C-M Racu et.al. (2020) [193,194]	2 DOFs (1 Rotational - 1 Rotational)	Electrical	Four Bar Mechanism	Plantarflexion Dorsiflexion Inversion Eversion	Rotary Potentiometers	Platform	• Passive Training; • Isokinetic Training.
(23)	Pneumatically Driven Stretching Machine for Ankle Dorsiflexion	Shiraishi et al. (2020) [195]	1 DOF (1 Rotational)	Pneumatic	Bellows Extension and Contraction	Dorsiflexion	Mechanical Limiter Sensors in Pneumatic Regulator Dynamometer and Joint Angle Meter (measurement—not part of robotic system)	Wearable	• Passive Training; • Resistance Training; • Isokinetic Training.

Table 1. *Cont.*

No.	Ankle Injury Rehabilitation Robot AIRR	Author (Latest Year) [References]	DOF (with Type of Motion)	Actuation	Mechanism	Covered Ankle Motion	Sensors	Platform/Wearable	Training Mode
(24)	Ankle Rehabilitation Mechanism Capable of Adjusting to Changes in Joint Axis	Szigeti et al. (2015) [196]	1 DOF (1 Rotational)	Electrical	Oldham's Coupling Mechanism Four-Bar Linkage.	Dorsiflexion Plantarflexion	N/A	Wearable	• Passive Training; • Isokinetic Training.
(25)	Customized Compliant Ankle Rehabilitation Device	Adolf et al. (2014) [197,198]	2 DOFs (1 Rotational)	Pneumatic	Pneumatic Muscles	Plantarflexion Dorsiflexion Inversion Eversion	Rotary Encoder Pressure/Force Sensor	Wearable	• Passive Training; • Perturbation Training; • Isokinetic Training.
(26)	Three -RRS Parallel Ankle Rehabilitation Robot	Zou et al. (2022) [199]	3 DOFs (1 Rotational- 1 Rotational- 1 Spherical)	Electrical	Branch Chains Crank Shaft Multiwedge Revolute Pair Spherical Joint	Dorsiflexion Plantarflexion Adduction Abduction Varus Valgus	Rotary Encoder (Installed in motor) Angle Sensors	Platform	• Passive Training; • Isokinetic Training.
(27)	Wearable Powered Foot Orthosis with Metatarsophalangeal Joint	Liu Y. et al. (2018) [200]	1 DOF (1 Rotational)	Electrical	Cylindrical Gear Bavel Gears Heteromorphic Gears Pivot shaft Parallel Mechanism	Dorsiflexion Plantarflexion	Heel Sensor (Contact Switch) Toe Sensor (Contact Switch)	Wearable	• Assistive Walking; • Passive Training; • Isokinetic Training.

3. Review Considerations

3.1. Strengths

The considerations for strengths of AIRRs are described as follows.

3.1.1. Capability

There will be three major perspectives in reviewing the existing AIRRs, in terms of capability, where the authors will study how much the AIRR is capable to fulfil most ankle motions and ankle exercises with the current structure. This can be determined through the number of the DOFs, the covered ankle motion, and the training mode. A higher number of DOFs, the covered ankle motion, and training mode for the AIRR, means the robot is of the highest capability to provide most of the ankle rehabilitation training by minimizing the amount of rehabilitation equipment needed to complete the rehabilitation.

Secondly, this category investigates the feedback capability of the AIRRs, where the implementation of the sensors was crucial for the AIRR system to ensure the safety and accuracy of the user and the sensors could provide a closed-loop feedback for the AIRR control system. This is important to ensure the AIRRs can be operated accurately and safely. The users and the system would know whether the motion of the foot platform (end effector) had exceeded beyond the limit of the ankle motion, or the robot was applying more than the necessary amount of force and torque to the injured ankle. This factor is crucial to ensure the effectiveness of AIRRs in quick recovery, while reducing the dependency on the strenuous conventional approach to physiotherapy and preventing re-injury. Additionally, the simple use of the mechanisms can determine the ease of control.

Thirdly, one of the features of AIRRs, such as platform-based or wearable-based, can also become an important indicator of a capability. With a platform based AIRR, it had the potential to perform various ankle rehabilitation exercises, such as muscle strength training and motion therapy. Furthermore, the ROM of the ankle-foot complex was restricted as they were bound in the limited workspace of the robot [10]. This allowed the AIRR to hold onto the actuated ankle completely, to make sure the injured ankle could experience the same motion or force that is usually carried out through the conventional treatment. With a wearable based AIRR, the patients could also apply the robot to improve the gait for stroke patients who experienced an ankle disability. This widens the robot's capabilities. The actuation features are ignored for this consideration as the selection of the electrical and pneumatic actuation, by the previous study, is based on the scope of the researchers. However, this feature is only limited to the discussion about the portability.

3.1.2. Portability

Portability is one of the considerations for the AIRR review, as portable AIRRs can help the therapist to move the equipment from one place to another and encourage a home-based rehabilitation. This will help patients to rehabilitate more frequently, as a visit to the hospital can be minimized. In this review, the type of actuation and mechanism was chosen to define the portability of the robot. For example, an electrical actuation system requires less additional equipment, compared to a pneumatic-based system, whereas a pneumatic system requires additional equipment, such as an air compressor to run the system. Nevertheless, the introduction of the compact air compressors available on the market has helped pneumatic-based machines to be more portable. In terms of the mechanism, the parallel mechanism and the linear actuator have helped AIRRs to be more compact and much easier to carry.

Features, such as the DOF, the covered ankle motion, sensors, platform/wearable, and training mode are ignored as these factors are not influencing the portability of AIRRs. The main reasons are: (1) the ability to fulfil the ankle motion and training mode, are a must for AIRRs, regardless of the portability, (2) due to its size, the application of the sensors would barely affect the weight of AIRRs, and (3) platform-based and wearable-based AIRRs have their purpose to fulfil certain ankle rehabilitation treatments, based on their structure. Thus, these features cannot be considered for portability.

3.2. Opportunities

The consideration for opportunities of AIRRs are described as follows.

3.2.1. Innovation

Features to determine the potential future innovation for the established AIRRs are the number of DOFs, the actuation, mechanism, ankle motion, sensors, wearable/platform, and training mode. These features focus on the hardware components that can be introduced for a future project. Furthermore, the opportunities in ankle motion are already covered under the scope of usage, therefore this feature will be ignored in the innovation consideration.

3.2.2. Scope of Usage

For the scope of usage, the covered ankle motion and training mode were chosen as these features were focused more on the potential additional exercises and training that can be introduced or need to be stressed for the potential AIRR project or upgrade. Other features, such as the DOFs, mechanism, and sensors are ignored as these features emphasize the hardware component of AIRRs instead of the exercise and training.

Table 2 presents summary comparative table on the ankle injury rehabilitation robot (AIRR)'s features with the strengths (Capability and Portability) and opportunities (Innovation and Scope of Usage).

Table 2. Summary comparative table on the ankle injury rehabilitation robot (AIRR)'s features with the strengths and opportunities.

AIRR Features	Strengths *	Opportunities *
DOF (with type of robot joints)	**Capability** - The majority of the selected AIRRs have 3 DOFs and above (14 AIRR) which should cover a minimum number of DOFs to cover all six basic ankle motions: **(2), (3), (4), (5), (7), (8), (10), (11), (12), (13), (16), (17), (19)** and **(26),** except **Rutgers (3)** 6 DOFs but covers four out of six basic ankle motions, **Reconfigurable Ankle Rehabilitation Robot (4)** 4 DOFs but covers four out of six basic ankle motions and **Three-PRS Parallel Robot (17)**-3 DOFs but covers four out of six basic ankle motion. - Additionally, one of the reviewed AIRRs is capable to fulfil four ankle motions with 1 DOF, such as **a One Degree of Freedom Ankle Rehabilitation Platform (21),** usually should be achieved with 2 DOFs or more. - Thirteen AIRRs have been selected to be operated under 2 DOFs and less **(1), (6), (9), (14), (15), (18), (20), (21), (22), (23), (24), (25), (27)** for which these AIRRs will be much easier to program their operations. **Portability** N/A	**Innovation** - In terms of the DOF, it is encouraging for future researchers to research fulfilling all basic ankle motions or more, by minimizing the number of DOFs as much as possible and eliminating any redundancy in the mechanism. - Exploration of the reconfigurability would be an added advantage, such as adding one or two DOFs to fulfil specific ankle motions as is achieved with the **Reconfigurable Ankle Rehabilitation Robot (4)** by Yoon et al. (2005). **Scope of Usage** N/A

Table 2. *Cont.*

AIRR Features	Strengths *	Opportunities *
Actuation	**Capability** - Nineteen AIRR are using electrical-based actuators: **(1), (5), (6), (7), (8), (9), (11), (12), (14), (15), (16), (17), (19), (20), (21), (22), (24), (26), (27).** - Electrical actuators are considered cheap and require no additional components, compared to the actuator. - Eight AIRRs using pneumatic based actuators**: (2), (3), (4), (10), (13), (18), (23), (25).** - The strength of using a pneumatic actuator is that the pneumatic muscle is compliant and lightweight, that allowing the natural interaction with the patients. **Portability** N/A	**Innovation** - The combination of electrical and pneumatic actuations can be one new thing to explore where future researchers can adapt both the pneumatic advantage of the intrinsic softness and the electrical advantage of the controlled precision. **Scope of Usage** N/A
Mechanism	**Capability** - Fifteen AIRRs have parallel mechanism, as part of its mechanism **(1), (2), (3), (4), (5), (7), (10), (12), (13), (15), (16), (17), (18), (21), (27).** - The strength of using a parallel mechanism was because the payload or weight was carried by several links in parallel, which reduced the payload-to-weight ratio. Thus, reducing the wear and tear of the manipulator is suitable for the ankle when its workspace is very limited. **Portability** - Four AIRRs use the linear actuation to drive the foot platform–**Ankle Rehabilitation Robot (ARBOT) (1), Wearable Ankle Rehabilitation Robot (11), Redundantly Actuated Ankle Rehabilitation Robot (15)** and **Movable Ankle Joint Stretching Device (20).** - This is beneficial for developing a compact AIRR, due to small rotational motion from the motor that can be translated into the linear motion of the linkage. This allows the AIRR to be compactly built and leads to portability. - The cable-driven mechanism was chosen for three AIRR–**Novel Parallel Robot for Ankle Rehabilitation (12), Redundant Pneumatic Muscles Cable-Driven Ankle Rehabilitation Robot (13), and Pneumatic Muscles-Driven Ankle Rehabilitation Robot (18),** where the weight of the driving linkage can be ignored and allows this cable-driven AIRR to be lighter, compared to rigid linkage driven AIRR.	**Innovation** - Continuation of the parallel mechanisms in future research is still relevant as the parallel mechanism is seen as the best approach to actuate the injured ankle. It is suggested that the of new parallel mechanisms would be strongly encouraged. - Implementation of the soft robotic mechanisms in AIRRs. - The cable-driven mechanism can be explored more but needs to address the ability to provide both the push and pull motions/forces on the actuated ankle. **Scope of Usage** N/A

Table 2. *Cont.*

AIRR Features	Strengths *	Opportunities *
Covered Ankle Motion	**Capability** - **Only a Pneumatically Driven Stretching Machine for Ankle Dorsiflexion (23) is the selected AIRR to fulfil one ankle motion.** - There are five AIRRs with two ankle motions-**(6), (14), (20), (24), (27).** - There are 11 AIRRs with the capability of four ankle motions—**(1), (3), (4), (7), (9), (15), (17), (18), (21), (22), (25).** - The majority of the reviewed AIRRs provide four ankle motions or less, since most of the ankle exercises involve dorsiflexion/plantarflexion and inversion/eversion - Additionally, less ankle motion to cover, means it is easier for the AIRR to control and actuate. - There are nine AIRRs with six ankle motions—**(2), (5), (8), (10), (11), (12), (13), (19), (26)** and **AssistON-ankle (16)** is the only AIRR with more than 6 ankle motions. - There are 10 AIRRs that can operate within six basic ankle motions or more. This is also a strength where these AIRRs can fulfil all the basic ankle motions for rehab. **Portability** N/A	- **Innovation** N/A **Scope of Usage** - The future researcher, can focus on more combinations of two or more basic ankle motions to fulfil some of the ankle training and exercise that require a combination of two or more ankle motions.
Sensors	**Capability** - Fourteen 27 AIRRS were using the force sensor or load cells in their system—**(1), (2), (3), (5), (9), (10), (12), (13), (15), (16), (17), (18), (20), (25).** - Application of the load cells or force sensors will help the AIRR to apply the right amount of force to the injured ankle, in order to ensure its effectiveness is the same as the conventional therapy. - There are three AIRRs with position sensors in their system–**Ankle Rehabilitation Robot (ARBOT) (1), Redundant Pneumatic Muscles-Cable-Driven Ankle Rehabilitation Robot (13), and Customized Compliant Ankle Rehabilitation Device (25).** - The position sensor is an advantage because this sensor can help to ensure the foot platform is positioned accurately, according to the procedures. - Six AIRRs use an angle sensor or inclinometer-**(9), (11), (12), (13), (14)** and **(26).** - The main advantage of using an angle sensor is the foot platform can provide the correct rotation during the operation. - Nine AIRRs have installed encoders in their system—**(1), (5), (7), (8), (9), (10), (12), (14), (19), (25), (26).** - This sensor is important as feedback from the rotation of the motors is needed. This is to ensure that the rotating motors can translate the right motion of the foot platform correctly. - Five AIRRs have installed torque sensors in their system—**(1), (6), (12), (13), (14).** - Torque is an important parameter in measuring the effectiveness of the ankle rehabilitation treatment, where the AIRR needs to apply the right torque on the actuated ankle, according to the procedures. **Portability** N/A	**Innovation** - Continuation of the installation and combination of the position, torque, and angle sensors would be beneficial for the accuracy of AIRRs, as the sensors can provide the necessary torque, position, and rotation angle of the foot platform. - Implementation of the mechanical sensor where the motion of the foot platform can be limited, by being independent from the system. - Continuous exploration using sensors to implement virtual reality treatment, where interaction between patients and AIRRs encourages recovery. **Scope of Usage** N/A

Table 2. *Cont.*

AIRR Features	Strengths *	Opportunities *
Platform/Wearable	**Capability** - Fifteen AIRRs have a platform-based structure— **(1), (3), (4), (5), (6), (8), (9), (12), (13), (15), (17), (18), (21), (22) and (26).** - Platform-based AIRRs have the advantage of performing certain ankle rehabilitation exercises, such as balancing. Unlike wearable based AIRRs, where the size of patients' lower limbs, apart from the foot size, must be taken into consideration. Platform-based AIRRs only need to consider the size of the patient's foot, which makes the ergonomic readjustment for the AIRR much easier. - Twelve AIRRs are wearable-based—**(2), (7), (10), (11), (14), (16), (19), (20), (23), (24), (25) and (27).** - Wearable-based AIRRs have one main advantage, in that they can provide walking aid rehabilitation, compared to the platform-based AIRRs. Contrasted with the platform based AIRR, this AIRR can be expanded in rehabilitating the lower limbs and not just limited to the ankle. The application for an improved gait for stroke patients can also be encouraged with wearable based AIRRs. **Portability** N/A	**Innovation** - The combination of platform-based and wearable-based mechanisms will provide more coverage on the ankle exercise, using only one AIRR. **Scope of Usage** N/A
Training Mode	**Capability** - All AIRRs will be involved in passive and isokinetic training or exercise where rehabilitation equipment will be used, during the passive rehabilitation stage and isokinetic is a type of exercise that uses a specialized machine, such as the AIRR. - Three AIRRs, such **as Ankle Rehabilitation Robot (ARBOT) (1), Novel Parallel Robot for Ankle Rehabilitation (12),** and **Redundantly Actuated Ankle Rehabilitation Robot (15)** have added active training, as a part of their rehabilitation activities. - Active exercise training is a great addition to the AIRR, where patients can try to rehabilitate themselves without interference by the AIRR. The role of the AIRR in this training stage would be data gathering on the ability of the patients to move their feet inside the AIRR. - Seven AIRRs can provide strengthening exercises—**(1), (3), (4), (7), (12), (15), (16).** - This approach helps patients to recover by strengthening the muscles of the injured ankle. - Three AIRRs can provide flexibility Exercises–**Rutgers Ankle (3), Reconfigurable Ankle Rehabilitation Robot (4), SUKorpion (7).** - Flexibility exercise is encouraged to fulfil all the necessary ankle rehabilitation motions, which will help to restore the ROM of the ankle. - Balance/proprioception exercises were provided by fives AIRRs—**(3), (4), (7), (9), (16).** - Balance/ proprioception features for the rehabilitation procedures, help to restore balance to the injured ankle. **Portability** N/A	**- Innovation** N/A **Scope of Usage** - For future researchers, assistive walking rehabilitation can be a good approach for treating the injured ankle, although, this exercise is limited to the wearable based AIRR. - Only a **Pneumatically-Driven Stretching Machine for Ankle Dorsiflexion (23),** from the studies mentions resistance exercises for the AIRR. The role of resistance training is important to improve the muscles of the injured ankle and encourage a faster rehabilitation. - Additionally, balance exercises or proprioception of the ankle are good to explore to improve the proprioception of the foot. However, this exercise is only limited to the platform-based robot. - Introduction to teaching and playback features in the future projects will allow the therapist to teach the AIRRs how to move and actuate properly, according to the actual physiotherapy session.

* The numbered rounded brackets refer to the allocated AIRR number not the reference number of the study.

4. Discussion

The purpose of the review is to evaluate the existing AIRRs, using strengths and opportunities from the SWOT analysis as an additional supplement to the already established guidelines, for future researchers to advance their research and development of AIRRs. Although the medical results were much more reliable in evaluating the feasibility of AIRRs, this approach is only useful if there is plentiful medical data available. However, in this case, not all sources that have been gathered are presented with medical data to demonstrate the feasibility of the AIRR that has been developed. Furthermore, most sources from the previous research were not undergoing clinical trials which could provide crucial medical data, to evaluate its effectiveness. In this review, the authors can only use the available critical technical information that can be gathered from the articles, to evaluate the AIRRs. Using this approach helps the reviewers to determine the features of the robot, according to its strengths, and help to predict by presenting potential opportunities that can be identified with the limited medical information available.

4.1. Strengths

The overall result, based on strengths, shows that the majority of the selected AIRRs had three DOFs and above, which should cover the minimum number of six basic ankle motions, although not all these three DOF AIRRs translate to a full six basic ankle motions. The actuation, the electrical and pneumatic actuators, and the platform-based, or wearable based indicators played their purpose, specifically in aiding the rehabilitation procedures in which the actuation and the selection of the structure for the AIRRs must be seen as equal in their respective advantages.

In terms of mechanism, the advantage of the parallel mechanism in AIRRs is the payload or weight being carried by several links, in parallel, which reduces the payload-to-weight ratio, thus reducing the wear and tear of the manipulator. Furthermore, its simple structure supported its end effectors in multiple areas, resulting in stifles. Similarly, the positioning errors had been 'averaged out' in each leg, thus the accuracy has been improved. In terms of control, the use of a parallel mechanism guaranteed an easier control and was easier to determine the movement of the robot, due to the non-cumulative joint error. Unlike the serial mechanism, the parallel mechanism can be highly efficient, due to the position of the motors close to the base, which means that the power from the motor was quickly transferred towards the base, resulting in fewer losses of power.

Additionally, the strength of using a cable-based AIRR, where the weight of the driving linkage can be ignored, allows this cable-driven AIRR to be lighter, compared to the rigid linkage driven AIRR, and using a linear actuation will allow the AIRR to be compact and easy to control. While the rigid linkages can provide additional support on the weight of the patients, thus allowing the need to support the weight-based exercise, such as balancing. In summary for strengths, in terms of the ankle motion, less covered ankle motion means less hassle to control the machine while the ability for the AIRR to fulfil all ankle motions would be a great advantage in reducing the dependency on a lot of ankle rehabilitation equipment required for the complete recuperation. The soft robotic mechanism can be a popular approach for the rehabilitation, as the soft robotic mechanism can adapt to patients' wearability and is safer for the human-machine interaction, as the mechanism is using soft materials to actuate the motion, instead of hard materials for the rigid links [201].

For the sensors, the use of load cells or a force sensor is one of the main strengths for AIRRs to apply the right amount of force to the injured ankle, based on the procedures. The addition of the position, angle, and torque sensors is also an advantage where these sensors can help to ensure that the foot platform position, rotation, and applied torque are correct.

Finally for training mode, apart from the passive and isokinetic exercise ankle rehabilitation, additional training modes, such as active exercise training, would widen the rehabilitation training scope and help to reduce the dependency on the rehabilitation equipment. The balance or proprioception exercise will be an added advantage to restore balance on the ankle.

4.2. Opportunities

The overall result, based on strengths shows that minimizing the number of mechanisms or reducing the number of DOFs, and yet being able to fulfil all basic ankle motions, would be encouraging in future research. Hopefully, the future mechanisms for AIRRs would be much simpler and easier to control. Secondly, the concept of reconfigurable AIRRs will allow AIRRs to provide additional DOFs or training modes to their overall operation, as the open structures of the robots (if designed) allow any possibility of additional structures to be added although reconfiguration, based on the size of the patient's foot, which has already been explored by the previous AIRRs. For the mechanism, the continuation of the parallel mechanism is still relevant in future research, with the introduction of the new mechanism. Additionally, the cable mechanism in AIRR research can be explored but must address issues on the pull/push motions on the actuated ankle.

The combination of the pneumatic and electrical actuation would be an excellent opportunity, where the advantages of electrical and pneumatic actuations can be combined into one AIRR. Additionally, if an AIRR can have both wearable and platform-based mechanisms, through a structure reconfiguration or structure integration, this will widen the ankle exercise treatment and reduce the amount of equipment needed to fully rehabilitate the ankle injury.

In terms of the covered ankle motion, a combination of two or more basic ankle motions has a great potential for future AIRRs, as some of the ankle rehabilitation exercises or training require more than two or more basic ankle motions. This provides good opportunities for future researchers who want to explore complicated ankle exercises but prefer to do them with as few ankle motions as possible. With this approach, time and effort will be committed to setting and programming much more complicated exercises, instead of fulfilling all basic ankle motions through simple exercises. For the sensor, a combination of the position, torque, and angle sensors will help the foot platform of the AIRR to be operated effectively, according to the rehabilitation procedures where the applied motion and force are crucial. The addition of a mechanical-based sensor would be an added advantage to ensure the foot platform will not exceed the required limit independently from the control system.

For the training mode of the AIRR, the addition of the assistive walking rehabilitation training exercises, resistance, and balance would provide a lot of choices in the rehabilitation stages for the patients. Additionally, with teaching and playback, AIRRs can overcome the problem of difficulty to actuate the platform, using offline programming, especially dealing with different sizes of feet. This is important as different sizes of feet patients require a slight adjustment of the movement to make sure their foot is actuating accurately. This has been accomplished as the robot will try to imitate the movement of the ankle of the patient while every movement will be recorded into the system.

5. Conclusions

The existing AIRRs can provide good alternatives for patients to improve ankle injury rehabilitation, thus encouraging a faster and more effective recovery. Some of the reviewed AIRRs that also provide active ankle rehabilitation exercises and expanded the scope of their ankle rehabilitation procedures using a robot. Likewise, the role of existing AIRRs is crucial to improve the range of motion, balancing, and muscle strengthening of the ankle, although the introduction of the robots will not replace the human touch from the physiotherapist altogether. Instead, this will strengthen the ankle rehabilitation procedures, where the users can have the opportunity to increase the frequency of the treatment.

The implementation of strengths and opportunities from a SWOT analysis, based on the technical point of view can help to elevate the benefits and expectations of AIRRs, from the perspective of internal and external factors. The factors of weaknesses and threats are a challenge to review from the existing bibliography, as some weaknesses and threats are part of the previous research scope. Adding weaknesses and threats will provide an unfair judgment for the researchers who devoted their time, cost, and efforts to make their mark in the AIRR research.

In addition, home rehabilitation plays an important role to increase the frequency of rehabilitation and reduce the role of doctors/therapists to a supervisory role, without the need for constant visits between patients and doctors/therapists. As the review was currently written during the COVID-19 pandemic, the dependency on getting to public buildings, such as clinics and hospitals, can be minimized with the introduction of home-based rehabilitation activities, that can be provided by rehabilitation robots. With this review, the potential benefits of the existing work can help future researchers to improve or to develop a much better AIRR.

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