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Ankle rehabilitation robots and its main features: a review

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Abstract. *Stroke, spinal chord injury, traumatic brain injury, sports injuries, traffic accidents, and congenital foot deformities such as clubfoot are the main causes of ankle disabilities, which cause its loss of motion and weakness. This condition leads to impaired patterns of gait, quality of life degradation, and daily life activity restrictions. To gradually recover the ankle joint's functionality, patients take long, repetitive, and intensive sessions of physiotherapy in specialized centers of rehabilitation. However, the traditional rehabilitation process has some limitations, such as: demanding a great number of physiotherapists; personnel fatigue; one-to-one patient and doctor assistance; and a lack of an objective and quantitative method of analyzing the patient's progression history during the whole period of therapy. Thus, the use of robotic devices to provide support in ankle rehabilitation comes as an alternative to solve or at least attenuate these problems. Such an alternative could relieve physiotherapists' exhaustion, allow therapists to aid multiple subjects at time, and assure an approach to measure, record, and store patients' data progress during the rehabilitation procedures. This review paper aims to report the leading researches on robotic devices to aid the ankle rehabilitation process. Another goal is to classify such surveyed devices according to their driving actuator, motion capabilities, security mechanisms, ankle axis rotation matching, control strategy, and degree of freedom. The method consists of researching the main articles at Scopus with "ankle", "rehabilitation" and "robot" as keywords since 2019. Results showed a variety of ankle rehabilitation devices that could be classified and presented as a table to ease the reader's analysis. The table contains some essential and relevant aspects of the researched devices. The primary highlight is the classification of each of these robotic devices according to its main attributes and features. Finally, it serves as a guide for ankle rehabilitation researchers who wish to compare different robotic manipulators based on many aspects and characteristics.*

Keywords: *ankle, rehabilitation, robotics, review, classification*

1. INTRODUCTION

The ankle joint complex of humans mainly consists of the tibia, fibula, talus and calcaneus, and it has three degrees of freedom, namely, dorsiflexion/plantarflexion (DO/PL), inversion/eversion (IN/EV), and adduction/abduction (AD/AB) (Dong *et al.*, 2021), as shown in Fig. 1.
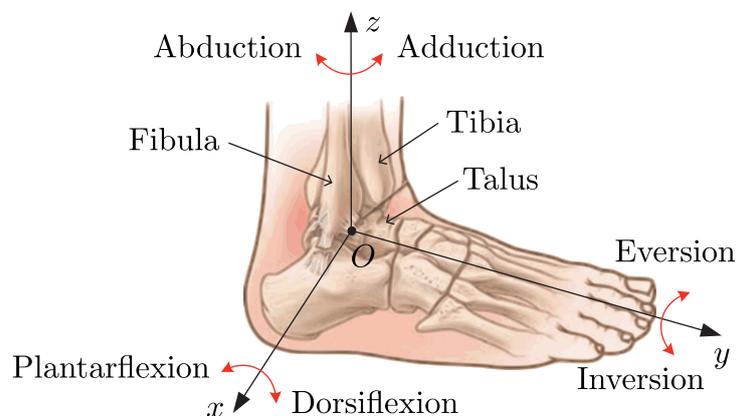

Figure 1: Structure of human ankle joint. Zhang *et al.* (2019).

It plays a fundamental role in many aspects of daily life such as weight distribution, shock absorption, foot-clearance, control the contact of the foot with the ground (Gomez-Vargas *et al.*, 2021), propulsion, lower limb coordination, adaptation to different environments, maintenance of stability (Martelli *et al.*, 2019), sustain the load of the whole body while exerting key forces during push-off, leg swing, and center of mass advancement during the human gait (Russo and Ceccarelli, 2020) (Gonçalves *et al.*, 2023).

However, ankle sprains, neurological injuries and congenital disorders can drastically compromise the ankle function, more specifically its motion. Accidents, diseases and conditions like traffic accidents, sprains (Yu *et al.*, 2014), cerebral palsy, stroke, spinal cord injury, traumatic brain injury (Gomez-Vargas *et al.*, 2021), multiple sclerosis (Schubert *et al.*, 2021), clubfoot and valgus (Zhang *et al.*, 2019) (Dong *et al.*, 2021) are the most frequent causes of ankle disabilities which implies a severe degradation of quality of life of many individuals around the world.

As said by Alipour *et al.* (2022), to recover the natural and healthy functionality of the ankle, patients take intense, exhaustive and repetitive rehabilitation exercises under the supervision of physiotherapists. Nevertheless, the rehabilitation process has some limitations and issues such as therapist fatigue, reduced number of physical therapy sessions, the non-repetitive nature of training sessions performed by different therapists, a lack of any objective method to record and analyze the patient's progress and recovery (Hussain *et al.*, 2016), the extreme dependency on the therapist's skills, one-to-one dependency (Ayas and Altas, 2016) and the requirement of plenty of time and patience concerning the patient and physiotherapist (Wang *et al.*, 2014).

With this set of problems described, robot manipulators came as an alternative to solve or at least mitigate these issues (Gonçalves and Rodrigues, 2021). According to Zhang (2016), Ayas and Altas (2016) and Jiang *et al.* (2019), ankle rehabilitation robots (ARR) can provide a group of advantages to patients and physiotherapists such as:

- Provide a rich stream of measurement data to aid the therapists quantify the improvement of the rehabilitation process;
- Enable therapists treat multiple patients at time;
- Quicken the patients' recovery;
- Spare physiotherapists from repetitive tasks;
- Avoid patients leaving the treatment by encouraging them with interaction training schemes such as serious game and virtual reality.

Many devices for ankle rehabilitation have been presented in literature, with different structures, configuration and working principles. To support researchers, scientists, designers and engineers, a categorization of these devices is essential. This leads to an extension of the overall comprehension of the state of art, allowing the researcher to compare different devices.

Thus, this paper proposes a classification of recent ankle rehabilitation robots that are present in the literature since 2019. Some fundamental and general features of the current robots will be highlighted and used as characteristics to classify the investigated devices. At the end, the reader will be able to a clear identification of the main characteristics of each researched device presented in this paper.

2. METHODOLOGY

Scopus was used, as one of the largest curated bibliographic abstract and citation databases today according to Baas *et al.* (2020), in order to apply a particular search strategy to gather a significant amount of papers to support this study. At first, an inclusion criteria was applied at the search platform in order to start the search task. After the search process, an exclusion criteria was used to filter the documents to finally gather all the remaining articles. To ease reader's understanding, the inclusion and exclusion criteria is presented in the following.

Inclusion criteria:

- Scopus as bibliographic database;
- Keywords: "ankle", "rehabilitation" and "robot";
- "Search Within" field present at the Scopus search platform was selected as "Article title, Abstract, Keyworks";
- Date range: 2019 to present.

It is a consensus to the researchers, as seen in Alipour *et al.* (2022), Ayas and Altas (2016), Liu *et al.* (2022), Racu and Doroftei (2016), Shi *et al.* (2019), Zhang (2016), Wang *et al.* (2021a), Zuo *et al.* (2020), Alnajjar *et al.* (2020), Chin *et al.* (2017), Khalid *et al.* (2015), Alvarez-Perez *et al.* (2019) and Zhetenbayev *et al.* (2022), that ankle rehabilitation robots are divided in two main groups:

- Standing/walking/exoskeletons/orthoses/wearable robots;
- Sitting/lying/stationary/platform robots.

According to Zhang (2016), exoskeletons are aimed at ankle rehabilitation together with gait rehabilitation and platform robots are focused only on ankle rehabilitation. Zhang (2016) proposed a hierarchy chart to divide and classify the ankle rehabilitation robots, which is shown in Fig. 2. In Fig. 2, DOF stands for Degree Of Freedom, A-PAR stands for actuated from above parallel ankle robots and B-PAR represents actuated from below parallel ankle robots. This study is focused only on searching platform-based robots, for that reason, all papers that present a device that is not classified as a platform robot were excluded.
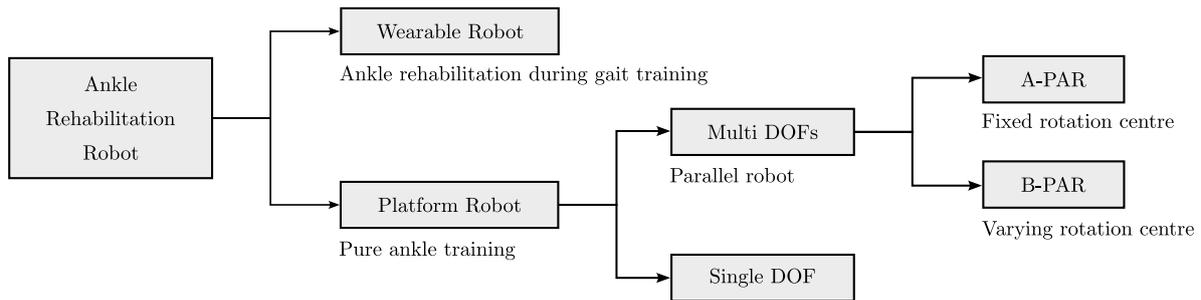
Figure 2: Hierarchy chart of existing ankle rehabilitation robots. Zhang (2016).

Exclusion criteria:

- Language: English;
- Document type: Article;
- Platform robots;
- Studies showing significant information related to the design of the robot;
- Studies that shows one of the following: 3D CAD model of the robot or a prototype.

A total of 20 papers were collected and they compose the object of study of this review.

3. RESULTS

Table 1 presents the review of the collected papers. The first column contains the citation of the particular article which can be checked in the section 6. The remaining columns consists of several features, which are considered the most important ones, of the ankle rehabilitation robots explored. To better understand the main features presented in Tab. 1, each one of them are presented and explained in the following paragraphs.

Degree of freedom (DOF) is the number of independent parameters needed to localize the device in a particular position. All researched robots develop one or a group of motions presented in Fig. 1. Some of them have translation capabilities, which explain why some devices have more than 3 DOF.

Focusing on ankle rehabilitation, the third column of Tab. 1 shows what group of ankle motions (Fig. 1) and its range of motion (ROM) the particular device is capable of produce in the rehabilitation process.

The actuation type column presents the driving instrument employed in the robot structure in order to produce its motion and conduce rehabilitation. The acronym PMA stands for Pneumatic Muscle Actuators.

In the field of rehabilitation, the exercise mode is often defined by the existence or not of muscular effort of the patient. The passive mode exercise stands for a kind of exercise where the patient do not exert muscular effort, usually the patient's limb is manipulated through the physiotherapist's manual force. The active mode exercise is the sort of exercise where the patient must move its limb to overcome a force to recover muscular strength.

The control strategy represents what are the variables the authors choose to control in order to accomplish the robot's motion and the rehabilitation process. GPI stands for generalized proportional integral controller.

To achieve safe rehabilitation performance and avoid secondary injury, the axis of rotation of the ankle rehabilitation robot must coincide or at least stay close to the actual patient's ankle axis. Some researchers contemplate this feature to the design of the rehabilitation robot and this functionality is explored and shown in Tab. 1.

Some articles only develop pure theoretical concepts and analysis while others present experimental analysis employing a prototype. Thus, the column "Prototype" declares if there is at least a figure of the prototype of the robot.

It is common in the robotics branch of knowledge, the use of a simple scheme of nomenclature to define and characterize a particular robot regarding the number of links, joint types and driving joints. Then, the column "Nomeclature" in Tab. 1 brings the name of each researched device. The terms R, U, P, S, C, P_a and HJ denote revolute, universal, prismatic, spherical, cylindrical, parallel quadrilateral and homokinetic joints respectively. The group of these terms express a particular link and the numbers before indicate its quantity. Underlined terms indicate the joint that is actively driven.

To ensure safety and avoid accidents during the rehabilitation, in events such as control issues, overload, human errors and other emergency incidents, some designers develop safety systems to release patient's limb to avoid critical accidents. Thus, the column "Safety system" inform if the particular robot has any emergency system to protect patient's limb.

It was left empty all the information related to the features presented in Tab. 1 that was unclear or missing in any specific article. Only clear and evident information, presented in the paper, was used to fill Tab. 1. Figure 3 shows a model or a prototype of all the researched robots found in the literature and presented in this study. The letters found in the first column of Tab. 1 before each citation, are associated with the letters found in Figure 3.

Table 1: Comparison of main features of different ankle rehabilitation robots found in the literature.

Paper	DOF	Motion and ROM	Actuation type	Exercise mode	Control strategy	Ankle axis matching capacity	Prototype	Nomenclature	Safety system
a) Qu *et al.* (2023)	4	DO/PL: 30°/45° IN/EV: ± 30° AD/AB: 25°/20°	—	—	—	Yes	No	(2-CRS+PU)&R	—
b) Zhetenbayev *et al.* (2023)	3	DO/PL IN/EV: ± 10° AD/AB: ± 10°	4 Linear electric actuators	Active Passive	Position control	—	No	—	—
c) Li *et al.* (2022)	3	All	2 Linear electric actuators 1 DC Servo motor	Active Passive	Trajectory tracking control	—	Yes	R-2UPS/RR	—
d) Liu *et al.* (2022)	4	DO/PL: ± 40° IN/EV: ± 40°	4 Linear electric actuators	Passive	Trajectory tracking control	Yes	Yes	2-UPU/RPU	Yes
e) Ortega *et al.* (2022)	2	DO/PL IN/EV	2 Stepper motors	Passive	GPI/Trajectory tracking control	—	Yes	—	—
f) Zou *et al.* (2022)	3	All	3 Low-speed torque motor	Passive	Position-speed control	Yes	Yes	3-RRS	—
g) Asín-Prieto *et al.* (2022)	1	DO/PL Active: 25°/55° Passive: 25°/55° Resistive: 15°/25°	1 Brushless DC motor	Active Passive Resistive	Position control	—	Yes	—	Yes
h) Wang *et al.* (2021b)	2	Case 1: All Case 2: DO/PL and IN/EV	2 Linear electric actuators	—	—	Yes	No	UPU/SPU	—
i) Dong *et al.* (2021)	3	All	2 Linear electric actuators 1 DC Servo motor	Passive Compliance exercise Isotonic exercise Active	Trajectory tracking control	Yes	Yes	2-UPS/RRR	Yes
j) Chen *et al.* (2021)	3	DO/PL IN/EV	—	Passive	Position control	—	No	3-PRS	—

Table 1 Continued: Comparison of main features of different ankle rehabilitation robots found in the literature.

| Paper	DOF	Motion and ROM	Actuation type	Exercise mode	Control strategy	Ankle axis matching capacity	Prototype	Nomenclature	Safety system
k) Guzmán-Valdivia *et al.* (2021)	1	DO/PL: 20°/45°	Motor	—	Trajectory tracking control	—	Yes	—	—
l) Zeng *et al.* (2020)	4	All	—	Static Dynamic	—	Yes	Yes	2-CPRR-PU/R	—
m) Russo and Ceccarelli (2020)	3	All	Servo Motors	—	—	—	No	S-4S$\underline{P}$S	—
n) Zuo *et al.* (2020)	3	DO/PL: 30°/45° IN/EV: ± 10° AD/AB: ± 36°	2 Linear electric actuators 1 Servo motor	Active Passive	Position control Impedance control	—	No	2-UPS/RRR	Yes
o) Akagi *et al.* (2020)	6	All	6 Linear electric actuators	Active Passive	—	—	Yes	—	—
p) Zhong *et al.* (2020)	—	—	2 PMA	—	—	—	Yes	—	—
q) Chang and Zhang (2019)	3	All	—	—	—	—	No	RRR-P$_a$RPS-RHJ	—
r) Zhang *et al.* (2019)	3	DO/PL: 30°/46.2° IN/EV: ± 23.5° AD/AB: ± 36°	2 Linear electric actuators 1 Stepper motor	Active Passive Human-interaction	Impedance control	Yes	Yes	2-U$\underline{P}$S/$\underline{R}$RR	—
s) Wang *et al.* (2019)	2	DO/PL: ± 30° IN/EV: ± 30°	2 Motors	—	—	—	Yes	2-S'PS'	—
t) Zang *et al.* (2019)	3	All	4 PMA	—	Voltage control	—	Yes	4-SPS/S	—
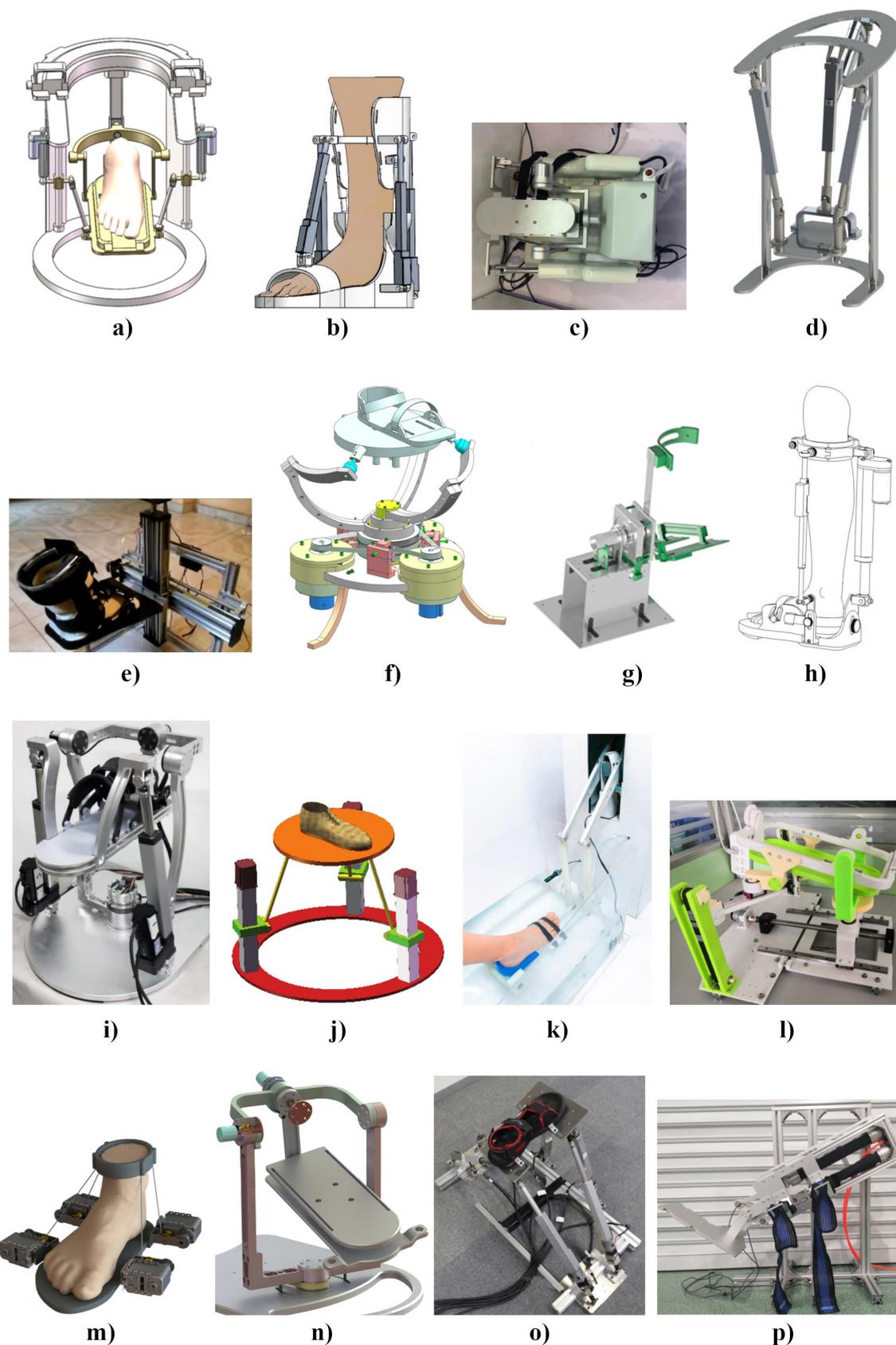
Figure 3: Model or prototype of the explored ankle rehabilitation robots. a) Qu *et al.* (2023) b) Zhetenbayev *et al.* (2023) c) Li *et al.* (2022) d) Liu *et al.* (2022) e) Ortega *et al.* (2022) f) Zou *et al.* (2022) g) Asín-Prieto *et al.* (2022) h) Wang *et al.* (2021b) i) Dong *et al.* (2021) j) Chen *et al.* (2021) k) Guzmán-Valdivia *et al.* (2021) l) Zeng *et al.* (2020) m) Russo and Ceccarelli (2020) n) Zuo *et al.* (2020) o) Akagi *et al.* (2020) p) Zhong *et al.* (2020).
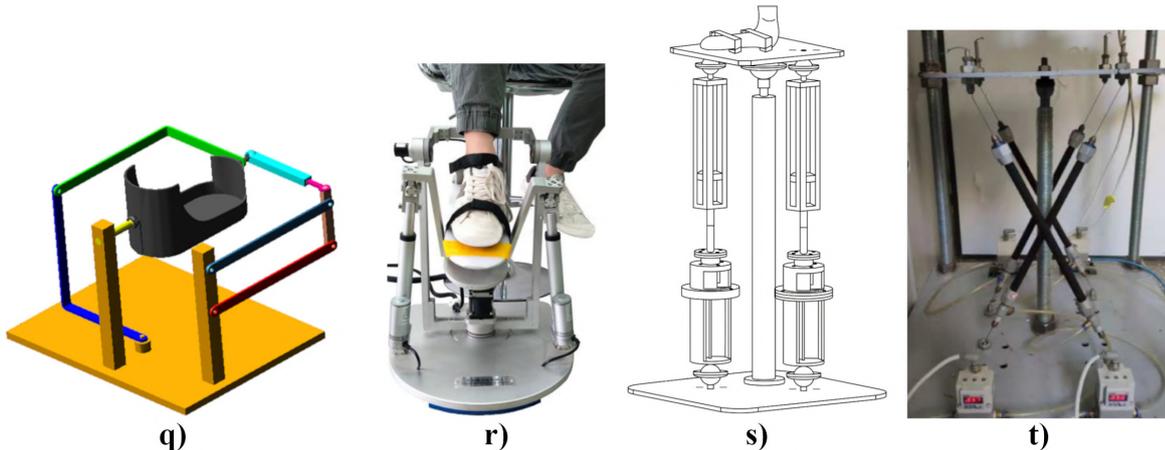
q)   **r)**   **s)**   **t)**

Figure 3 Continued: q) Chang and Zhang (2019) r) Zhang *et al.* (2019) s) Wang *et al.* (2019) t) Zang *et al.* (2019).

4. DISCUSSION AND CONCLUSIONS

This study presents a review of platform ankle rehabilitation robots existent in the literature since 2019 until mid year 2023. It was intended to explore the design of these devices and classify some of their basic functionalities and relevant characteristics. A group of main features were listed and used to typify the researched devices. Twenty articles were selected and analyzed in this work. To reach the objective in an evident manner, it is presented a table which classify the reviewed robots, as well as a figure showing a model or a prototype of some of the explored devices.

Regarding the type of motion that each particular robot covers, it is noted that the majority of researched devices can provide DO/PL motion. This happen because DO/PL are one of the most important motions in daily activities and notably in gait, as seen in Liu *et al.* (2022) and Zhang *et al.* (2019). Thus, it is reasonable to expect that the developed devices cover at least this group of motion.

It could be seen that the architecture 2-UPS/RRR was found in 3 of the collected articles and compared to others, it was prevalent. Nothing was found in the literature to explain this circumstance. Analyzing the actuation type and motion of these 3 articles, in Tab. 1, it could be seen that every device consist of 2 linear electric actuator and 1 motor; and they can produce the 3 ankle motions. With that in mind, it can be perceived that this architecture can provide all the 3 desired ankle motions with minimal quantity of actuators. This could explain the popularity of this architecture.

It was not common to see safety systems described in the collected papers, as shown in the last column of Tab. 1. Just 4 of all researched articles describes security systems in their designs. The same could be said about the concern of the designers about the ankle axis matching capability. Table 1 shows that only 7 studies described clearly the design and interest in match the axis rotation of the platform to the axis of the patient's ankle.

Possible gaps found in this literature review are: few devices have ankle axis matching capacity and safety system, lacks a clear design for manufacturability practice, it isn't clear if the devices offer a human machine entertainment platform or a data acquisition feature. Besides ankle axis matching capacity and safety system, which were explained before, design for manufacturability, human machine interaction and data acquisition are some characteristics that are not clear or were missing in the researched papers. The design for manufacturability is important to ease the manufacturing in a possible future step of the robot. Human machine integration for entertainment is important to decrease dropout rates of rehabilitation process. The data acquisition is important to assess the patient's progress in the treatment, bringing useful numeric info over time, which evaluated by a physiotherapist, quantifies each patient's evolution.

Finally, there are several important characteristics that the engineer must consider when designing an ankle rehabilitation robot. Some of them were previously discussed and explored in this paper: the motion capabilities (*i.e.* DO/PL, IN/EV and AD/AB) and its capacity of covering the range of motion of a healthy ankle, the type of actuation and its quantity, the control strategy and the sort of exercises it could develop, the coincidence of ankle and robot axis of rotation and a safety system to prevent secondary injuries in emergency situations. In addition, other attributes are also relevant such as: virtual reality, lightweight and small size device. In order to entertain and avoid patient's abstention it is common the development of a virtual reality interface united with serious game. Lastly, low mass and small size are often desired features in the mechanical design of products. Thus, it is interesting that an ankle rehabilitation device has lightweight and small size aspects. This ensures the ease of transportation and the requirement of little space in centers of rehabilitation.

Future works consist of developing a new ankle rehabilitation robot. The conceptual design embraces a low cost device, covering all three basic ankle motions (without compound motion), employing a windshield wiper motor as a driver unit and human machine integration through serious games. This article comprehends the first effort of developing a new ARR in which this literature review came as foundation that can support decision-making and gap identification.

5. ACKNOWLEDGEMENTS

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