

Reviewing effectiveness of ankle assessment techniques for use in robot-assisted therapy

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Abstract—This article provides a comprehensive review of studies that investigated ankle assessment techniques to better understand those that can be used in the real-time monitoring of rehabilitation progress for implementation in conjunction with robot-assisted therapy. Seventy-six publications published between January 1980 and August 2013 were selected based on eight databases. They were divided into two main categories (16 qualitative and 60 quantitative studies): 13 goniometer studies, 18 dynamometer studies, and 29 studies about innovative techniques. A total of 465 subjects participated in the 29 quantitative studies of innovative measurement techniques that may potentially be integrated in a real-time monitoring device, of which 19 studies included less than 10 participants. Results show that qualitative ankle assessment methods are not suitable for real-time monitoring in robot-assisted therapy, though they are reliable for certain patients, while the quantitative methods show great potential. The majority of quantitative techniques are reliable in measuring ankle kinematics and kinetics but are usually available only for use in the sagittal plane. Limited studies determine kinematics and kinetics in all three planes (sagittal, transverse, and frontal) where motions of the ankle joint and the subtalar joint actually occur.

Key words: ankle measurement, ankle stiffness, clinical effectiveness, disability assessment, qualitative assessment, quantitative assessment, range of motion, rehabilitation device, reliability, robot-assisted therapy.

INTRODUCTION

Ankle injuries are very common both in sports and daily life [1–5]. In New Zealand, about 100,000 claims

related to ankle sprains were made to the Accident Compensation Corporation in 2000 and 2001 at a cost of an estimated 31.8 million New Zealand dollars [6]. From 2002 to 2006, a total of 82,971 ankle sprains were identified in the National Electronic Injury Surveillance System database, and an estimated 2.15 ankle sprains occurred per 1,000 person-years in the United States [7]. Neurologic injuries such as stroke and spinal cord injuries also cause various ankle problems [8–9]. Ankle injuries cause complications such as edema, disuse atrophy, and arthrosis unless treated properly [10]. Additional symptoms usually include chronic pain, reduced range of motion (ROM), weak strength, and increased joint stiffness, as well as severe functional limitations [5,11].

Clinicians often use a qualitative assessment method to assess ankle impairment based on a predefined scoring

Abbreviations: 3D = three-dimensional, CAI = chronic ankle instability, FAAM = Foot and Ankle Ability Measure, FADI = Foot and Ankle Disability Index, FFI = Foot Function Index, IAROM = Iowa Ankle ROM, ID-BM = inverse dynamics based method, JOA scale = Japanese Orthopedic Association's foot rating scale, MSE = manual spasticity evaluator, PT-BM = potentiometer and torquemeter based method, ROM = range of motion.

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system. When quantitative methods are undertaken, these most commonly include the use of a goniometer or dynamometer. The goniometer is a tool to assess ankle ROM [12–13] and the dynamometer is usually used to assess ankle strength [14–15]. Other devices have been developed for measuring ankle stiffness, for monitoring the progress of a rehabilitation program, or for tracking changes in joint stiffness [16–17]. These measurement tools can guide clinicians in determining the most effective intervention.

There have also been significant advances in robotic rehabilitation in an effort to reduce the strain on the clinician. Various robot-assisted ankle rehabilitation devices have been developed in recent years [18–23]. They usually lack the function of real-time ankle assessment that should be included in a robot-assisted ankle rehabilitation program to allow the robot to adjust the control strategy for a specific rehabilitation stage. Having a better understanding of the clinical tools that are most effective in providing intervention and how they might provide quantitative inputs for robot-assisted ankle rehabilitation is necessary to develop a robotic rehabilitation device that engages all users.

This review seeks to critically compare various published studies in terms of the development, application, reliability, and validity of existing ankle measurement devices and techniques. It will provide a better understanding of the requirements for a real-time assessment strategy implementable within a robot-assisted rehabilitation program that can be used throughout the rehabilitation process.

METHODS

Search Strategy

Only English-language articles published from January 1980 to August 2013 were searched in the following six databases: Scopus, Web of Science, ScienceDirect, Academic Search Premier, Embase, and MEDLINE (OvidSP). The search terms were “Ankle*” AND “Performance OR Function OR Disabilit* OR Disorder* OR Injur* OR Spastic* OR Stabilit* OR Stiff* OR Torque OR Moment OR Strength OR Kine* OR Dynamic* OR Dorsiflexion” AND “Evaluat* OR Assess* OR Measur* OR Examinat*.” Additional searches in Google Scholar and SpringerLink were further conducted for the latest

studies as an important supplement. Valuable references listed in relevant publications were also screened.

A total of 411 articles were identified initially. The first two rounds of screenings were conducted based on titles and abstracts, respectively. Studies considered to meet the predefined inclusion criteria were included in the final analysis and the others were excluded. Discussion among authors resulted when inclusion of certain articles was questionable. The **Figure** describes the selection process.

Inclusion and Exclusion Criteria

This study aims to review existing ankle assessment techniques that can provide necessary information to allow for an evaluation of improvement during ankle exercises that are implemented using robot-assisted rehabilitation. The review attempts to better understand all methods of evaluation, including qualitative and quantitative assessment of ankle recovery level. Articles involving ankle performance or functional qualitative assessment methods such as the Foot Function Index (FFI) and Foot and Ankle Disability Index (FADI) were included. All quantitative studies assessing ankle performance or function (including ankle disability level, kinematics, and kinetics) were included. All articles had to include trials involving either normal ankle or injured

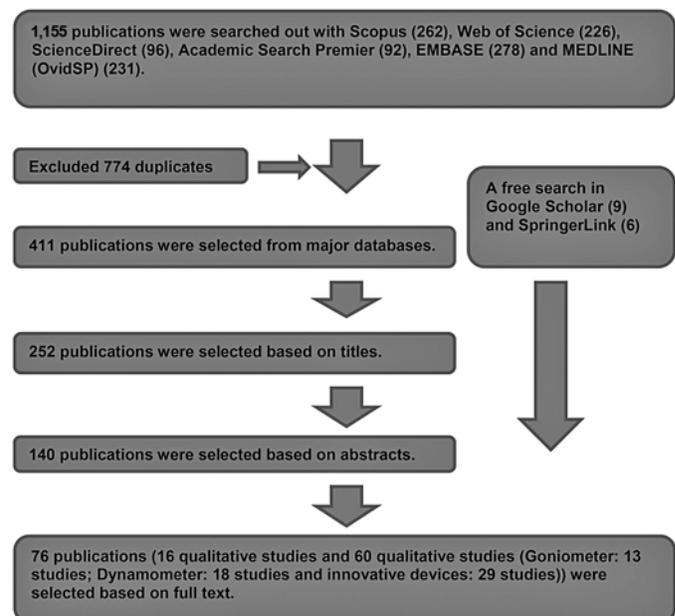


Figure. Flow diagram of selection process for final review.

ankle. Trials assessing animal ankle performance or function were excluded due to significant differences between the animal ankle and the human ankle. Studies involving management or identification of ankle injuries and those related to emergencies were excluded, as were invasive ankle measurement techniques. Observation-based physiological assessment techniques were excluded due to unreliable accuracy [24]. Image-based methods were also excluded because they cannot be used to evaluate functional improvement in ankle injury in combination with robot-assisted therapy. Image-based techniques that examine kinematics in vivo such as magnetic resonance imaging, computed tomography, and X-ray tend to be expensive and not implementable in a typical robotic system, though they can be used for identification of ankle injury [25–26]. In this review, we do not seek to comment on the ability to detect ligament tears (it is assumed that the correct identification of ankle injury has already occurred) but rather to examine the functional improvement before, during, and after rehabilitation interventions. The data extraction was applied in a similar way as another review conducted by Zhang et al. [27].

RESULTS

After excluding studies involving invasive measurement techniques [28–30], animal-based methods [31–32], image-based methods [25–26,33–35], diagnosis of ankle injuries [2,36–39], and management of ankle injuries [3,40–44], there were a total of 76 publications identified for further analysis. These were divided into two main categories: 16 qualitative studies [45–60] and 61 quantitative studies. These 60 studies were further grouped into 13 studies using goniometers to measure ankle joint ROM [12–13,61–71], 18 studies involving dynamometers to measure ankle strength (4 studies about handheld dynamometers [15,72–74] and 14 studies about isokinetic dynamometers [14,75–87]), and 29 studies with innovative ankle measurement techniques developed to measure various ankle parameters, including ankle ROM, strength, torque, and stiffness that may be used for real-time assessment of patient improvement [16–17,88–114].

Assessment techniques requiring specialist training were included in 16 qualitative studies. An additional 31 quantitative studies involving goniometers or dynamometers were also found that mainly measure either ROM or

strength—both parameters easily measured by a robot. Additional studies that provide information about parameters that can potentially be implemented in robot-assisted training were the main focus of this article and included 29 quantitative studies. A total of 465 subjects participated in these 29 quantitative studies, of which 19 studies were conducted on less than 20 participants (**Table 1**). These participants comprised both healthy volunteers and patients with diverse ankle injuries.

DISCUSSION

Qualitative Ankle Assessment Techniques

With a view to understanding the clinical functional scales and how an assessment of improvement is conducted (and to better understand the accuracy requirements for measurement by robot-assisted techniques), the following sections describe the qualitative measurement techniques.

Scoring Systems

The traditional method of describing ankle injuries was to group the assessment results: good, fair, and poor [115]. In recent years, more accurate scoring systems have been developed for ankle performance or function assessment. SooHoo et al. demonstrated that the FFI (a self-administered index consisting of 23 items) was a reasonable measure to monitor ankle status by examining its level of correlation to the Medical Outcomes Study Short Form-36 on 73 patients [50]. Karlsson and Peterson presented a scoring scale based on the subjective assessment of the patient's symptoms and level of function, and the evidence on 148 patients demonstrated that this system could be used to evaluate ankle function before and after treatment of ankle joint [45]. More sophisticated, Kaikkonen et al. proposed a performance test protocol and scoring scale for functional evaluation of ankle injuries based on both subjective patient feedback and clinical ankle examinations, including the measurement of ROM, laxity of ankle joint, and muscle strength [48]. This method showed excellent reproducibility and the total score correlated obviously with isokinetic ankle strength, subjective opinion of recovery, and subjective functional assessment on 148 patients. All these systems involve subjective assessment from either physiotherapists or patients.

Niki et al. proposed new scales with improved expressions for Japanese people based on the clinical rating

Table 1.

Reviewed studies of quantitative ankle measurement techniques.

Study	Subjects (n)	Subject Characteristics	Subject Age (yr)	Methods	Measures	Reliability
Schepers and Veltink, 2006 [101]	1	Healthy subject	Not stated	Instrumented shoes	Ankle moment	RMS difference of GRF: 19.1 N; RMS difference for CoP: 17.9 N
Schepers et al., 2007 [104]	1	Healthy subject	Not stated	Instrumented shoes	Foot and ankle dynamics	RMS difference of GRF: 0.012 ± 0.001 N/N; CoP estimation RMS difference: 5.1 ± 0.7 mm; RMS difference of heel position estimates: 18 ± 6 mm; ankle moment RMS difference: 0.004 ± 0.001 Nm/N; RMS difference of estimated power: 0.02 ± 0.005 W/N
Rouhani et al., 2011 [109]	22	12 patients with ankle osteoarthritis, 10 healthy subjects	Patients: 58 ± 13 ; healthy subjects: 61 ± 13	Ambulatory system consisting of plantar pressure insole and inertial sensors	Ankle force, moment, and power	High repeatability (CMC > 0.7)
Keating et al., 2000 [93]	31	10 unimpaired physiotherapy students, 21 subjects with stroke	Impaired group: 75.4 ± 8.0 ; healthy group: 24.3 ± 3.9	Lidcombe Template	Magnitude and direction of force applied to dorsiflex foot	Highly reliable for both groups ($r > 0.92$)
Moseley and Adams, 1991 [91]	15	5 staff members, 5 people with CVA, 5 adults with head injury	Not stated	Lidcombe Template	Angle and force in ankle dorsiflexion	ICC for combined group data: 0.97; intertester agreement: 77%
Wilken et al., 2004 [97]	29	17 subjects (repeatability), 12 physical therapy graduate students with no history of lower-limb pathology (validity)	Repeatability group: 53 ± 14 ; validity group: not stated	IAROM device	Ankle dorsiflexion ROM	Average ICC: 0.92; mean correlation: 0.96
Wilken et al., 2011 [110]	29	Validity testing: 12 participants (6 M, 6 F; height: 1.7 ± 0.1 m; body mass: 72 ± 12 kg); Intertester reliability: 17 participants (7 M, 10 F; height: 1.7 ± 0.1 m; body mass: 88 ± 21 kg)	Validity group: 23 ± 3 ; Intertester reliability group: 52 ± 15	IAROM device	Ankle dorsiflexion motion and stiffness	Validity testing ICC values: 0.95–0.98; reliability testing ICC values: 0.90–0.95; ICCs for ankle joint dorsiflexion stiffness: 0.71 (knee in extended position) and 0.85 (knee in flexed position)
Peng et al., 2004 [99]	11	6 children with CP, 5 healthy children	Children with CP: 6–19	MSE	Ankle ROM, elastic stiffness, and Tardieu R1 catch angle	Not stated

Table 1. (cont)

Reviewed studies of quantitative ankle measurement techniques.

Study	Subjects (n)	Subject Characteristics	Subject Age (yr)	Methods	Measures	Reliability
Peng et al., 2011 [108]	22	12 children with CP with ankle spasticity, 5 healthy children, 5 healthy adults	Children with CP: 4–19; healthy children: 12–14; healthy adults: 21–31	MSE	Ankle ROM, elastic stiffness, and Tardieu R1 catch angle at different velocities	High reproducibility with ICC = 0.82; Pearson $r = 0.81$; $p = 0.002$
Roy et al., 2007 [103]	4	2 M and 2 F (height: 147.3–177.8 cm, weight: 45–74 kg, passive ROM: 64°–94°)	24–40	Anklebot	Ankle stiffness	Errors dorsiflexion: 0.75°; errors plantar flexion: 0.89°; correlation coefficient: 99.61
Zinder et al., 2007 [105]	20	Healthy subjects (10 M, 10 F; height: 177.16 ± 6.01 cm [M], 167.15 ± 5.98 cm [F], weight: 80.79 ± 13.53 kg [M], 71.10 ± 11.87 kg [F])	M: 28.97 ± 5.66; F: 25.67 ± 3.48	Unique ML swaying cradle device	Inversion/eversion ankle stiffness	Trial-to-trial reliability ICC coefficient: 0.96 (SEM of 2.05 Nm/rad); day-to-day reliability ICC coefficient: 0.93 (SEM of 3.00 Nm/rad)
Kobayashi et al., 2010 [16]	2	Patients with stroke	49 and 34	Manual ankle assessment device	Ankle stiffness	Not stated
Kobayashi et al., 2011 [107]	10	Subjects with hemiplegia (all M)	54.3 ± 8.4	Manual ankle assessment device	Ankle stiffness and ROM	High reliability, with ICC values >0.97
Sung et al., 2010 [106]	46	Sex-matched healthy subjects	≥20	Intelligent stretching device	Ankle stiffness	Reliability ICC coefficient of ankle stiffness between-day for both examiners: 0.77 (SEM of 0.05) for right ankle and 0.76 (SEM of 0.04) for left ankle
Lorentzen et al., 2012 [113]	83	46 healthy volunteers (16 F), 14 volunteers with SCI (1 F), 23 volunteers with MS (14 F)	Healthy volunteers: 32 ± 7; volunteers with SCI: 48 ± 12; volunteers with MS: 53.3 ± 12.0	Portable Neurokinetics RA1 Rigidity Analyzer	Ankle joint stiffness	High intrarater reliability (ICC for volunteers with SCI: 0.60–0.89; ICC for controls: 0.63–0.67); interrater reliability (ICC for volunteers with SCI: 0.70–0.73; ICC for controls: 0.61–0.77)
Loram and Lakie, 2002 [94]	15	Healthy subjects (8 M, 7 F)	20–68	Ankle stiffness measuring apparatus	Ankle stiffness	Coefficient of variation: 5%
Casadio et al., 2005 [100]	18	Healthy subjects (9 M, 9 F)	21–31	Force platform and motorized footplate apparatus	Intrinsic ankle stiffness during quiet standing	Not stated
Ji et al., 2004 [98]	4	Healthy subjects (2 M, 2 F)	29–70	Computational method with MATLAB	Ankle postural stiffness	High coefficient values of determination

Table 1. (cont)

Reviewed studies of quantitative ankle measurement techniques.

Study	Subjects (<i>n</i>)	Subject Characteristics	Subject Age (yr)	Methods	Measures	Reliability
Mirbagheri et al., 1996 [17]	11	8 M, 3 F	Not stated	Parallel-cascade system identification method	Ankle dynamic stiffness and separation of intrinsic and reflex components	High intrasubject reliability ($r > 0.8$) but high inter-subject variability
Forster, 2003 [95]	1	Normal subject	Not stated	Bilateral electro-hydraulic actuator system	Dynamic ankle joint stiffness during standing	Not stated
Kearney et al., 1990 [89]	15	Healthy subjects	23–39	System identification technique	Ankle dynamics	Intrasubject reliability was as good as or better than most clinical measures, and intersubject variability was somewhat larger
Weiss et al., 1990 [90]	3	Patients recovering from fractures of lower leg (2 M, 1 F)	28, 28, and 50	System identification technique	Ankle dynamics	Ankle dynamics measures were qualitatively similar to those of normals: stiffness was low in region near mid-range and increased obviously near limits of movement
Chesworth and Vandervoort, 1988 [88]	10	Healthy subjects (all F)	26–46	Ankle torque measurement system	Passive ankle mechanical stiffness	High reproducibility
Nordquist and Hull, 2007 [102]	1	Experienced snowboarder (height: 185 cm; weight: 74.8 kg)	Not stated	“Elbow-type” ISL	Dynamic ankle motion in field environment	RMS errors: 0.59° for orientation, 1.00 mm for position; maximum measurement deviations: 0.05° in orientation, 0.10 mm in position
Fong et al., 2012 [111]	12	6 cadaveric specimens, 6 subjects (all F; height: 1.60 ± 0.04 m; body mass: 54.8 ± 5.8 kg)	25.8 ± 2.7	Mechanical jig	Ankle supination and pronation torque	Good internal consistency of trials was obtained with typical errors of 0.3 (standing position) and 0.1 (sitting position)
Winegard et al., 1998 [92]	10	5 M, 5 F	73–92	Footplate apparatus	Voluntary isometric strength and evoked isometric twitch properties, M-wave amplitude, and passive tension	Mean reliability coefficient of all measurements on the dorsiflexion and plantar flexor muscle groups was 0.91 ± 0.05
Naito et al., 2012 [114]	4	Healthy subjects (all M; height: 170.3 ± 5.2 cm; weight: 61.5 ± 15.4 kg)	30 ± 11.5	Estimation of muscle length parameters based on measurement data	Passive ankle joint moment vs ankle angle; ankle muscle length	Predicted data are consistent with measured data

Table 1. (cont)

Reviewed studies of quantitative ankle measurement techniques.

Study	Subjects (n)	Subject Characteristics	Subject Age (yr)	Methods	Measures	Reliability
Giacomozzi et al., 2003 [96]	21	Healthy volunteer (1 M; height: 185 cm; weight: 75 kg) assessing experimental setup, 20 healthy volunteers (height: 168.6 ± 8.8 cm; weight: 71.0 ± 11.3 kg) for investigating ankle muscular functionality	Setup volunteer: 28; experimental group: 50.4 ± 14.6	Measurement device for obtaining kinematic characterization and isometric loading of ankle under different working conditions	Ankle kinematic and dynamic characterization	High linearity and overall accuracy are found in desired torque ranges, and inaccuracies are found in kinematic measurements
Knight and Weimar, 2012 [112]	26	13 subjects (5 M, 8 F) with history of single lateral ankle sprain, 13 healthy subjects (9 M, 4 F)	21.46 ± 1.17	Fulcrum device	Dynamic inversion speed	High reliability was found for time to maximum inversion (ICC = 0.81) and mean inversion speed (ICC = 0.79)

CMC = coefficient of multiple correlations, CoP = center of pressure, CP = cerebral palsy, CVA = cerebral vascular accident, F = female, GRF = ground reaction force, IAROM = Iowa Ankle ROM, ICC = intraclass correlation coefficient, ISL = instrumented spatial linkage, M = male, ML = medial/lateral, MS = multiple sclerosis, MSE = manual spasticity evaluator, RMS = root-mean-square, ROM = range of motion, SCI = spinal cord injury, SEM = standard error of measurement.

systems established by the American Orthopedic Foot and Ankle Society and the Japanese Orthopedic Association's foot rating scale (JOA scale) [54]. Reliability analysis on 65 clinicians and 610 patients was further conducted by Niki et al. [55], and the results showed that this newly established standard rating scale and the JOA scale are highly reliable, to some extent, which demonstrated its population-specific characteristic.

In contrast, two studies did not show positive effects for a certain group of people. Ansari et al. found that reliability of the Modified Tardieu Scale in the assessment of poststroke ankle plantar flexor spasticity was not high [46], and Campanini et al. demonstrated that the treatment of ankle spasticity for patients with cerebral vascular accident could not rely on the Ashworth score completely [47].

Other studies investigated and compared various qualitative ankle assessment systems. Haywood et al. summarized seven disease-specific assessment methods of ankle performance (Ankle Joint Functional Assessment Tool, Clinical Trauma Severity Score, Composite Inversion Injury Scale, Kaikkonen Functional Scale, Karlsson Ankle Function Score, Olerud and Molander Ankle Score, and the Point System) and concluded that any measure should be used with caution until appropriate evidence is provided [49]. However, further investi-

gation into the effectiveness of functional outcome scores specific to patients was necessary, which was also supported by Farrugia et al. [53].

Foot and Ankle Disability Index and Foot and Ankle Ability Measure

Although the FADI and Foot and Ankle Ability Measure (FAAM) belong to the category of scoring systems, they were discussed independently since a systematic review [56] identified them as the most appropriate outcome instruments to quantify functional limitations in patients with chronic ankle instability (CAI).

Hale and Hertel advocated the use of the FADI and FADI Sport self-report instruments in clinical care and research applications in young adults with CAI [57], and these instruments appeared to be reliable in assessing functional limitations. Further, Wikstrom et al. concluded that self-assessed disability got from these systems was greater in subjects with CAI than uninjured groups, which showed their patient-specific characteristic [60]. More advanced, the FAAM (as the later version of the FADI) showed satisfactory validity and reliability on groups with various ankle injuries [51]. Martin et al. developed the FAAM for measuring region-specific and non-disease-specific function of the foot and ankle and

concluded that it was a reliable and valid measure of physical function for individuals with a wide array of musculoskeletal foot and ankle disorders [58]. Further, Carcia et al. concluded that the FAAM may be used to detect self-reported functional deficits related to CAI [59], and Cosby and Hertel verified its reliability and validity on a male basketball player with inversion ankle sprain [52]. As for the region-specific attribute, direct comparison among different populations is quite necessary, although some versions have proved to be reliable. For example, Mazaheri et al. conducted tests on 93 Persian patients and found that the FAAM was a reliable and valid measure to quantify physical function [51]. Therefore, it can be summarized that the FADI and FAAM are usually reliable, but larger sample sizes with a greater diversity of populations and various ankle injuries should be investigated in future research.

Taking all studies into consideration, it can be concluded that these scoring systems are usually region-specific and disease-specific; thus, a universally designed method with convincing validity and reliability is essential. Further, these currently available systems usually require participants to conduct a series of functional activities and answer subjective questionnaires and then rate function on a prespecified scale based on ankle performance. This assessment, which usually lasts a few minutes or longer, makes it difficult for the realization of real-time evaluation when used in robot-assisted therapy, though some of the techniques and questions may be valuable in engaging the user in understanding the therapy being undertaken, especially during a robot-assisted program.

Quantitative Ankle Assessment Techniques

To better be able to quantify functional improvement using robot-assisted therapy, quantitative measures are required. These should incorporate all aspects of ankle control, including ankle kinematics and kinetics such as ROM, muscle strength, and joint stiffness. This section discusses the tools (standard techniques and innovative techniques) to measure these aspects of functional control.

Standard Techniques

Ankle range of motion. The ankle ROM is an important functional parameter that relates to the efficiency of gait. An effective measurement of ankle ROM in all three planes is important to better understand functional improvement. For this reason, ankle ROM is frequently assessed clinically. This section discusses devices that

can be used for determining ankle ROM and provides important information about requirements in the development of an assessment method implementable with a robot to assist ankle therapy.

Goniometers have been considered as the standard method of ankle ROM measurement with a satisfactory reliability, especially for ankle dorsiflexion [12–13,61–66,68–71]. One study showed its poor interrater reliability in ankle joint dorsiflexion [67], and measures using goniometry have been shown to be tester dependent [110]. However, Wilken et al. reported that the validity and repeatability can be problematic due to goniometer alignment, as well as potential variations in location and magnitude of forces applied to the foot [97]. To address these limitations, the Iowa Ankle ROM (IAROM) device allows angular measurements at predetermined force levels using a digital inclinometer and a handheld force gauge to measure ankle dorsiflexion ROM in a clinically friendly and cost-effective way [97,110]. The clinical test on 29 participants proved its repeatability and validity, but the application combined with robot-assisted therapy is restricted due to the manual operation of a handheld force gauge.

Ankle strength. Ankle strength is the amount of force ankle muscles can generate. The ability to generate force is necessary for all types of movement.

A hand dynamometer is usually used to measure grip and pinch strength and to perform muscle fatigue studies. Some studies have demonstrated that handheld dynamometers can be reliably used for measurement of ankle strength [15,72–74]. Different from the normal application, there is an innovative handheld dynamometer using a torque wrench and a goniometer that can measure static ankle angle and moment reliably and precisely [74]. Unfortunately, for the same reasons as the IAROM device, the manual operation of handheld dynamometer impedes its adoption when combined with robot-assisted therapy.

The isokinetic dynamometer is widely used during the various phases of rehabilitation. It is a precision-based electrical instrument that measures the performance of various muscle groups in the body. Isokinetic dynamometers including the Biodex dynamometer, the Cybex Norm, and the Kin Com II dynamometer in some studies have been demonstrated as the gold standard for measurement of ankle strength [14,75–79,81–87]. One study, however, showed that the validity of ankle inversion and eversion torque measurement using a manufactured

prototype ankle inversion and eversion attachment device on the Kin Com II dynamometer was questionable [80]. In addition, there are two studies [79,86] that assessed passive ankle stiffness with the isokinetic dynamometer by calculation [86] that presented satisfactory validity and reliability by clinical tests on 15 subjects. Although isokinetic dynamometers can be used for measuring ankle ROM, strength, and even stiffness, the main limitation is that ankle measurement and assessment is usually available only in the sagittal plane.

Innovative Techniques

Ankle torque and stiffness. Ankle stiffness is an important mechanical parameter that indicates the moment required for rotation and the resistance to an external perturbation [116–117]. Devices and techniques specifically to assess ankle stiffness have been developed. The working principles of most of these systems are similar. The system normally includes an actuator to generate rotation torque, a potentiometer to measure the angular displacement, and torque sensors to measure ankle moment. During tests, patients are usually required to move their ankles with different speeds, and the ankle stiffness will be calculated as the derivative of torque over angular displacement. Several of these systems have been evaluated in clinical settings, and the results showed that these types of devices can be a useful tool in the clinical assessment of ankle stiffness.

The Lidcombe template consisting of a spring balance and a perspex sheet ruled with parallel lines was adopted in Moseley and Adams and Keating et al. to measure the angle and force in ankle dorsiflexion, showing high reliability between testers [91,93]. Lorentzen et al. investigated the accuracy and reliability of a portable Neurokinetics RA1 Rigidity analyzer used for measuring ankle stiffness on 83 participants [113]. Results showed that it could potentially be a useful diagnostic tool for measuring ankle stiffness, although it was originally developed to test elbow rigidity. These devices require manual operation from physiotherapists; thus, their applications when combined with robot-assisted therapy are restricted.

Direct ankle assessment techniques using the potentiometer and torquemeter are easier to apply during robot-assisted therapy. Two studies constructed a manual device to measure ankle joint ROM and stiffness in patients with stroke and showed promise for clinical application [16,107], of which Kobayashi et al. [107] pre-

sented an improved design based on the device in Saleh and Murdoch [24]. The manual spasticity evaluator (MSE) was used for the quantitative evaluation of ankle spasticity and stiffness in two studies that conducted clinical trials on six children with cerebral palsy, five typically developed children, and five typically developed adults [99,108]. The results showed that ankle spasticity assessment could be more accurately performed using MSE. These two devices also need manual drive when measuring ankle stiffness, but this limitation can be easily overcome using a motor or other actuators.

Ankle stiffness can also be determined by measuring torque and joint angles in a more sophisticated way. A bilateral electro-hydraulic actuator system with position and torque transducers was used in Forster to measure dynamic ankle joint stiffness during upright human stance [95]. Sung et al. used an intelligent stretching device for ankle stiffness measurement [106]. They applied system identification techniques to characterize dynamic joint properties, including joint stiffness, viscous damping, and foot inertia properties during small-amplitude perturbations. Forty-six sex-matched healthy subjects participated in the trial, and results showed that this method was reproducible and consistent in ankle dorsiflexion and plantar flexion measurements. Chesworth and Vandervoort demonstrated that the proposed ankle torque measurement unit consisting of a potentiometer and a strain gauge could be a useful tool in the clinical assessment of passive ankle stiffness [88].

Different from single-plane assessment, Giacomozzi et al. developed a device for ankle kinematic and kinetics characteristics in three planes [96]. This device measured the three-dimensional (3D) movement of the foot with respect to the shank and evaluated torques around the three articular axes based on the measured position and moment information from transducers. Some studies also focus on ankle stiffness in quiet standing or postural control. Loram and Lackie used an inverted pendulum with a position transducer and a torque cell to measure ankle stiffness in quiet standing [94]. Casadio et al. used a device consisting of a motorized footplate mounted on a force platform for the direct of intrinsic ankle stiffness in quiet standing [100]. Ji et al. proposed a computational method to evaluate postural stiffness through ground reaction forces [98].

From a biomechanical perspective, quantitative assessment of ankle muscles and ligaments based on measured joint kinematics and kinetics is also necessary.

Ankle stiffness is mainly determined by grouping all muscles and ligaments surrounding the joint in which the passive component is the result of their viscoelastic properties [118]. Unfortunately, there have only been a few studies in which the muscular-skeletal properties of the ankle complex are considered. Naito et al. [114] applied a musculo-skeletal structure with a Hill-type muscle model for calculating individual muscle length based on the data from the device used in Kobayashi et al., and the results from four healthy subjects suggested its success [16,107]. A kinematics-based ankle model with major muscles and ligaments can be a promising approach to study passive ankle torque or stiffness, and comparisons with traditional methods in terms of accuracy should be conducted.

These ankle stiffness measurement methods applied different measuring techniques and thus the applicable scopes varied. The majority of these studies were able to assess ankle stiffness only in the sagittal plane, while a unique medial/lateral swaying cradle device in Zinder et al. was developed to measure inversion and eversion ankle stiffness with a satisfactory validity and reliability [105]. More directly related to robot-assisted therapy, the anklebot showed its potential to estimate ankle stiffness in three planes, although only tests in dorsiflexion and plantar flexion have been conducted [103]. Another two limitations of these studies are the small sample sizes and the lack of reaction forces acting on the device.

In summary, ankle stiffness assessment techniques mainly consist of direct measurement using the potentiometer and torquemeter based method (PT-BM) and an inverse dynamics based method (ID-BM) to determine the kinematics using reaction forces as the inputs. Some studies used the handheld dynamometer to estimate ankle stiffness [74,86]. **Table 2** is presented to analyze their prospects when used in robot-assisted therapy. The hand-

held dynamometer based method is subject to manual operation, to some extent, which affects the measurement accuracy. PT-BM cannot be used in parallel robots due to the use of the torquemeter that is usually installed between the power producer and the load. In other words, three potentiometers as well as three torquemeters for 3D ankle assessment are required. By contrast, the ID-BM is promising when combined with robot-assisted therapy. 3D ankle assessment using a 6-axis load cell will be available, but the validity and reliability need to be analyzed prior to use.

Other ankle kinematics and kinetics. Although ankle ROM, strength, torque, or stiffness have been measured quantitatively based on various devices and techniques, there are still some devices developed that can measure certain parameters not common in clinical application. For example, Knight and Weimar developed a fulcrum device to measure dynamic inversion speed, and the data from 26 participants showed high reliability for assessing maximum inversion and mean inversion speed [112].

In addition to these devices commonly used in the laboratory setting, three studies [101,104,109] developed ambulatory measurement systems of foot and ankle kinematics and kinetics in the sagittal plane, of which two studies [101,104] assessed instrumented shoes on healthy subjects. Results showed good correspondence between the proposed system and the reference, and another study also showed good reliability but with a different ambulatory ankle kinetics measurement system on 12 patients and 10 healthy subjects [109]. Additionally, a new instrumented spatial linkage was used in Norquist and Hull to measure dynamic ankle joint motion, and data from an experienced snowboarder demonstrated its utility in a field environment [102]. These ambulatory measuring techniques showed their potential in certain activities.

Table 2.

Prospect analysis of handheld dynamometer based method (HD-BM), potentiometer and torquemeter based method (PT-BM), and inverse dynamics based method (ID-BM) when used in robot-assisted therapy.

Method	Advantages	Disadvantages	Prospect in Robot-Assisted Therapy
HD-BM	Simple	Manual operation	Poor
PT-BM	Reliable	Restricted by robot structure and usually only measures in single plane	Reasonable
ID-BM	3D ankle assessment	Validity and reliability of 3D ankle assessment are not clear	Good

3D = three-dimensional.

Identification methods are commonly used to estimate ankle mechanics (passive and active stiffness) based on measured information. Kearney et al. used a system identification method to estimate ankle mechanics based on measured information from a potentiometer and a torquemeter [89]. Tests on 15 young adults showed that it had a good intrasubject variability and a somewhat larger intersubject variability. Mirbagheri et al. [17] described a parallel-cascade system identification method that had similar variability with Kearney et al. [89] when used to determine the intrinsic and reflex contributions to dynamic ankle stiffness. Further, Weiss et al. tried to monitor the mechanical consequences of soft tissue injury based on joint dynamics, and tests on three patients demonstrated its promise in clinical application [90].

To summarize, while Rome concluded that ankle joint dorsiflexion assessment was controversial in terms of measurement accuracies due to different study designs [119], most quantitative ankle measuring techniques have proved to be reliable for a certain individual or group. However, they were usually available for only ankle dorsiflexion and plantar flexion under passive motion in terms of kinematics and kinetics. Studies involving direct comparison in terms of reliability and validity among different devices and techniques are also lacking. Studies with less than 10 participants should be further validated with a larger sample size in the future.

Ideal Measurement Device for Use with Robot-Assisted Therapy

An ideal system to evaluate functional improvement using robotic assessment would include 3D assessment in terms of kinematics and kinetics.

In general, goniometers and dynamometers have been used commercially and can be considered standard tools for measuring ankle joint ROM and muscle strength but are not used to measure other attributes of functional improvement after ankle injury. Both ROM and strength can readily be measured using robotic techniques. Dynamometers and goniometers should be used as the gold standard with which to compare when testing reliability and reproducibility of robot measurement techniques. For torque or stiffness measurements, a combination of a 6-axis load cell and a parallel robot shows great potential for 3D ankle assessment during robot-assisted therapy. Further, a kinematics-based ankle model with major muscles and ligaments looks promising when used to study the passive components. A combination of 3D measure-

ment and the model-based method allows for differentiation between the active and passive components.

Kinematic and kinetic parameters of measurement are diverse, with no consensus as to device, technique, clinician expertise, or even whether to test passive or active motion. Studies involving direct comparison in terms of reliability and validity among different devices and techniques are important to better understand how these can predict function in the future. Further research should also focus on analyzing real-time ankle muscle and ligaments parameters in all three planes based on measured ankle kinematics and kinetics information. A robot assessment technique can be developed that is consistent in all aspects of kinematic and kinetic measurement, allowing for consistency for both before and after intervention and additionally among different patients.

Limitations of Robot Assessment

Robots are actuated manually or through the use of motors, linear actuators, and/or rotary actuators, which influence measuring accuracy. One study shows that difficulty existed in controlling the velocity applied to the ankle and the applied force during manual assessments, especially during high velocity or high ankle resistance conditions [120]. Comparisons among other actuators are lacking. Another study suggests that accurate movement control can lead to more reliable measurement outcomes [16]. Therefore, an accurate motion control system is necessary for developing a reliable and repeatable ankle assessment device.

Limitations of Search Strategy

An attempt was made to include all studies related to ankle measuring techniques. It is assumed that these selected studies used different participants. Other publications may exist where “foot,” “lower extremity,” or “lower limb” are identified as a key term instead of ankle. However, these may lead to potential incomplete searches, as well as some constraints like publication dates and languages.

CONCLUSIONS

While most qualitative ankle assessment systems have been shown to be reliable, they are usually region-specific and disease-specific; thus, a universally designed method with convincing validity and reliability is essential.

Further, the assessment items usually involve functional ankle tests, questionnaire answers, and clinical ankle examination, which make the generation of immediate evaluation results (real-time monitoring from a robotic perspective) difficult.

Most quantitative ankle assessment techniques are reliable in measuring ankle kinematics and kinetics but are usually only available for the sagittal plane. Limited studies determine kinematics and kinetics in all three planes, where motions of the ankle joint and the subtalar joint actually occur [5]. Once these kinematics and kinetics are better understood, online modeling may allow for alteration of interventions or control strategies during robot-assisted therapy based on real-time ankle characteristics. In addition, these innovative ankle assessment devices were usually evaluated with no more than 30 participants and should be further validated with a larger sample size. Direct comparison among different devices and techniques for a specific ankle parameter should also be conducted to determine what could be the ideal effective ankle assessment tools in a clinical environment.

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