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HOME-BASED ANKLE REHABILITATION SYSTEM: LITERATURE REVIEW AND EVALUATION

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Graphical abstract

Abstract

Ankle sprain Injury is one of the most common ankle injuries due to domestic or sporting accidents. There is a need for greater demand for quick and effective ankle rehabilitation system (ARS). Nowadays, research on ARS has gained a great attention than manual clinical method in medical areas such as orthopedic injuries, pediatrics sport medicine and industrial services. It can improve the treatment conditions by reducing the dependency of doctors' supervision, help patient with less movable to have home-based rehab exercise and help to speeds up recovery. There are currently available ARS that can provide effective ankle rehabilitation treatment such as Visual, Non-Visual and Robot-aided. In this paper, the critical review of ARS is conducted to evaluate the effectiveness of ARS in terms of provided setting criteria. The strengths, weaknesses, opportunities and threats of each ARS is discussed and compared to identify the most suitable home application of ARS for ankle sprain patient. From the comparison, the most suitable home application ARS is the visual marker-less based ARS system which give user-friendly, efficiency, validity in performance and cheaper cost.

Keywords: Ankle Injury, Ankle Rehabilitation System (ARS), Visual-Based Rehabilitation, Robot-based Ankle Rehabilitation System

Abstrak

Kecederaan buku lali yang terseliuh adalah salah satu daripada kecederaan buku lali kaki yang paling utama disebabkan kemalangan domestik atau kemalangan dari bersukan. Terdapat keperluan untuk permintaan yang lebih besar untuk sistem pemulihan buku lali kaki (ARS) yang cepat dan lebih berkesan. Pada masa kini, kajian mengenai sistem pemulihan buku lali kaki telah mendapat perhatian yang besar berbanding dengan kaedah klinikal dalam bidang perubatan seperti kecederaan ortopedik, perubatan sukan pediatrik dan perkhidmatan perindustrian. Ia boleh menambahbaik rawatan dengan mengurangkan kebergantungan kepada pengawasan doktor, membantu pesakit yang kurang kemampuan bergerak untuk mengadakan latihan pemulihan di rumah dan membantu untuk mempercepatkan pemulihan. Pada masa ini terdapat ada sistem pemulihan buku lali kaki yang boleh memberikan kesan yang baik kepada rawatan pemulihan buku lali kaki seperti Visual, Bukan-Visual dan Bantuan Pemulihan Robot. Dalam kertas ini, kajian kritikal sistem pemulihan buku lali telah dijalankan untuk menilai keberkesanan sistem pemulihan buku lali dari segi kriteria yang disediakan. Kekuatan, kelemahan, peluang dan ancaman untuk setiap ARS dibincangkan dan berbanding untuk mengenal pasti aplikasi rumah yang paling sesuai untuk ARS kepada pesakit buku lali kaki terseliuh. Dari perbandingan, ARS aplikasi rumah yang paling sesuai adalah sistem ARS ketiadan penanda berdasarkan visual yang memberikan mesra pengguna, kecekapan, kesahihan dalam prestasi dan berkos lebih murah.

Kata kunci: Kecederaan Buku Lali, Sistem Pemulihan Buku Lali, Pemulihan Secara Visual, Sistem Pemulihan Buku Lali Melalui Robot

1.0 INTRODUCTION

Ankle sprain is a common musculoskeletal injury in which the ligaments of the ankle partially or completely tear due to sudden stretching [1]. Ankle sprain account for almost half of all sports injuries and is a common reason why athletes take time off from activities [2]. Other than sports injuries, ankle sprain also account in the daily activities such as effects of previous ankle injury, impaired balance/postural control, and muscle strength/range-of-motion deficit [2]. Thus, ankle sprain is the common and critical injury as shown in the report from American Academy of Orthopaedic Sursgeons (AAOS).

In year 2012 AAOS Report, 25,000 people who experienced ankle sprain required admission to the hospital every day. Additionally, there are number of studies [3, 4] that show high occurrence rate for ankle sprain in sports [3, 5]. Fong DTP *et al.* [6] suggest that ankle is the most common injury related to sports and 24 out of 70 types of sports are related to ankle sprain. Lamb *et al.* [7] show that between 15% and 20% of all sports injuries are related to ankle sprain. Also, about 73% of athletes have suffered recurrent sprains [8]. In fact, Zafran *et al.* suggest that without critical diagnosis more than 40% of ankle sprain related cases can lead into chronic ankle instability [9]. These statistics suggest that ankle sprain is one of most common and critical injury experienced by people.

Ankle injury needs to be treated according to guidelines to prevent chronic ankle injury and instability [10]. An *R.I.C.E* guideline is one of the methods that can help to treat ankle injury; R.I.C.E stands for:

- *Rest* – The ankle must be immobilized by not walking on it. In this treatment, ankle brace can help to control swelling and adds stability while the ligaments are healing.
- *Ice* – This method is used to keep down the swelling.
- *Compression* – This method help to control swelling as well as immobilize and support your injury.
- *Elevate* – the foot will be by reclined and propped it up above the waist or heart as needed.

Nevertheless, rehabilitation process still need for every ligament injury after ankle sprain treatment. This needs to be done otherwise ankle sprain will not heal completely and cause re-injury [10]. However, there is no quantitative measurement output that could be used to adjust exercise difficulty and to measure progress over time [11]. Also due to current method of rehabilitation, patients require constant visit to the hospital which decrease the potential for frequent rehabilitation at home. Thus, there is a need for independent home based Ankle Rehabilitation System (ARS). With this system, the goal is to enable ankle sprain patients to regain the highest possible level of independence. This can be done by reducing dependency on treating the injury in hospital alone and continuing the treatment at home. However, some existing ARS are not portable, bulky and heavy. This leads to the increasing demand for compact, lighter and portable ARS.

With portable ARS research, health service can be enhanced to provide reliable, yet high quality services with positive treatment outcomes [12]. The development of ARS is to overcome the problem of limited number of medical experts' to patients' ratio. For example, this ARS can be implemented by introducing motion rehabilitation that can capture the actual motion of the ankle using devices that are easier to set up by patients. This will allow a patient to rehabilitate ankle sprain without the need of therapist which in turn will reduce the number of doctors' to patients' ratio. Still, there is a need to review the effectiveness of current ARS which is critical to determine whether these systems can provide better treatment for ankle rehabilitation.

The purpose of this paper is to review on the current ARS highlighting its effectiveness. Moreover, the existing systems have demonstrated its strengths to help to accelerate tracking designs recovery in human ankle motion. Unfortunately, much weakness still remains open, due to the complexity of human ankle motion and the existence of error in measurement. Besides that, the current reviews of ARS are not comprehensive. Most current reviews focus on robotic based[13, 14], non-visual based [15-17] and visual based [18] ARS specifically and respectively. Discussions among robotic based, non-visual based and visual based ARS are not comprehensively reviewed in current review. This review covers all three parts of ARS, gives an overview for the researchers to identify and choose specific research area in ARS. This paper is also highlighting the most suitable home application of ARS for ankle sprain patient.

This paper is organized as follows: In Section 2, types of ARS based on ankle sprain injury will be reviewed. In section 3, 4 and 5, we will discuss the Robot-Aid ARS, Non-Visual Based ARS and Visual Based ARS respectively. The comparison of the current ARS is discussed in Section 6. Finally, Section 7 is the conclusion.

2.0 ANKLE REHABILITATION SYSTEM

ARS is a remedy process to improve the abnormal motion back to the normal motion of foot and ankle. This normal motion of foot and ankle is based on the anatomy of human foot and ankle joint.

2.1 Anatomy of Human Ankle Joint

The human ankle joint plays an important role in maintaining the balance of an individual during a gait. It is the most complex movement of lower limb joint due to its 6 degree of freedom (DOF) in x, y and z direction. Therefore, it is capable of rotational motion about all three anatomical planes as shown in Figure 1. Based on the morphological motion of ankle joints (Figure 1), ankle sprain is the most frequent ankle injuries [19]. There are three types of ankle injuries: ankle sprain (ligament stretched), ankle fracture (bone fractured) and ankle strain (musculo-tendinous stretched) [20]. An untreated ankle sprain may lead to chronic ankle instability [20]. The severe ankle sprain injuries might include a serious bone fracture that, if untreated, could lead for troubling complications [20]. Thus, rehabilitation of a sprained ankle must begin immediately under correct procedures.

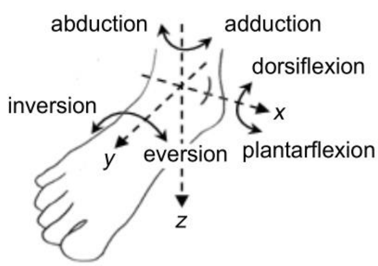


Figure 1 Morphological Motion of the human ankle joints

2.2 Ankle Sprain

A sprained ankle can occur to every one: athletes and non-athletes, children and adults. The chance of getting ankle sprain is higher if a person takes part in sports and physical fitness activities. This shows why ankle sprains are very common among basketball players and responsible for a large amount of time lost in rehabilitation [6, 7, 21-24]. The ankle sprain not only occurs in sports activities but also in domestic activities such as simply stepping on an uneven surface or stepping down at a certain angle. This injury occurs when ligaments at the ankle are over-stretched or torn, typically excessive motion in inversion (Figure 2) and plantar flexion directions (Figure 1) [21, 25].

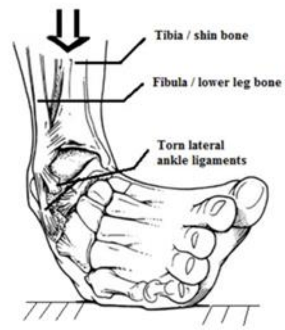


Figure 2 Ankle Sprain

The recovering process of ankle sprain has its standard medical protocol of ankle rehabilitation according UHN Toronto [26]. It generally begins with the immobilization of the affected ankle in order to reduce swelling and to stop effusions. Once active effusion has ceased, non-weight bearing range of motion (ROM) exercises should be carried out to stimulate the healing of ligaments and to reduce muscular atrophy. As the patient develops full weight bearing capability, strength training exercises are commenced to allow strengthening of the muscles around the ankle to prevent future injuries. As the patient improves further, proprioceptive training will be implemented to enhance the patient's sense of joint position and joint motion in maintaining balance during a gait [27]. This rehabilitation training can be better with the introduction of ARS.

The objectives of ARS are to restore optimal function of the injured ankle area, to return the athlete to competition quickly and safely, to compare to clinical ankle rehabilitation technique and to prevent re-injury. Ankle sprain usually takes relatively long time to recover (around 4-26 weeks), which depends on its severity, type of injury and type of activities [28]. ARS is divided into two types: Clinical ARS and Technological ARS as shown in Figure 3. This division is based on the some others diseases rehabilitation system such as stroke rehabilitation [29, 30], Parkinson rehabilitation [31], Upper-limb rehabilitation system [32], [33], [34], [35], and Lower-limb rehabilitation [36-38].

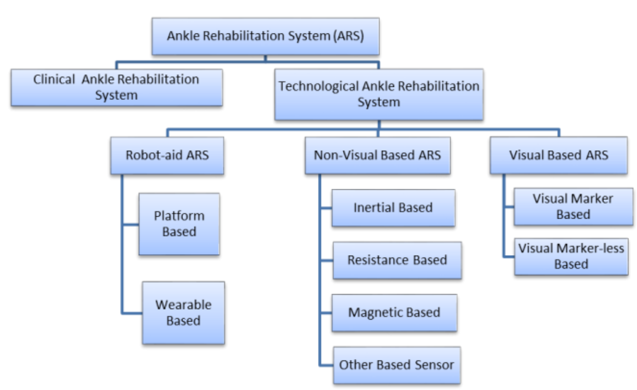


Figure 3 Classification of ankle rehabilitation system

The Clinical ARS is the traditional methods for ankle sprain recovery. All ankle sprains, from mild to severe, require four phases of recovery [39]:

1. Initial phase – Involves reduction of swelling by rest, elevation, ice in combination with compression, ultrasound and electrotherapy.
2. Early Rehabilitation – ROM of the ankle joints will be restored to normal range using manual treatment and kinetography. Also in this stage elastic bands, foam rollers and wobble boards will be used. In addition, towel will be used for self-stretching of the ankle ligamentous system to increase dorsiflexion.
3. Late Rehabilitation – Training of muscle strength and neuromuscular endurance.
4. Functional phase – This stage will involve jumping and running.

These four phases of recovery need continuous monitoring from the doctor from time to time. However, the simple equipment used in phase 2 are unable to provide analysis values (reading of angle, ROM, and velocity for ankle motion during exercise) and justification on ankle recovery. The Clinical ARS begins on the day of injury and continues until pain-free gait and activity are attained [40]. There are four components of clinical ankle rehabilitation exercises; they are ROM rehabilitation, progressive muscle-strengthening exercises, proprioceptive training and activity-specific training [3].

In contrast, Technological ARS is developed based on the clinical ankle exercises with supported technological aid such as sensors, actuators, cameras, markers and etc. Furthermore, it is divided into Robot-aid ARS, Non-visual Based ARS and Visual Based ARS. Robot-aid ARS provides assisted motion to move the ankle under proper direction, angle and velocity of its movement. Non-visual based ARS provides tracking on ankle measurement for analysis such as direction, angle, acceleration, and force but without external assistance on its movement. Visual based ARS provides a graphical display for ankle motion analysis in term of position, direction, angle and velocity, without external assistance on its movement.

3.0 ROBOT-AID ARS

The Robot-aid ARS is a system that helps to rehabilitate patients' ankle using robots or automation. Recently, voluntary repetitive exercises administered with mechanical assistance of robotic rehabilitators have proved effectively in improving movement ability in populations. This is shown by improving patients' ROM as the system has good repeatability and accuracy compared to conventional method of rehabilitation. Additionally, the system can enhance patients' ankle strength and improve patients' walking endurance by introducing resistive features from the ankle robot [14]. This system is suitable to be implemented during early and middle rehabilitation stage of the ankle as patients are incapable of moving on their own ankle due to the damage of ankle's ligaments [39].

As ROM and muscle strengthening require repetition and accuracy, these features can be provided by Robot-aid ARS [41–43]. Robot-aid ARS also incorporate individual sensor technologies to conduct "sense-measure-feedback" strategies by sensing the movement of the ankle and measure the actual position, force or distance of the ankle relating to the end effector. Finally with these measurements, the robot will decide whether the end effector of the robot is operating correctly or the actuator needs to be adjusted according to the right position. This should be implemented in short time to improve the efficiency of the robot. These sensors can help to improve the delivery of the treatment by increasing the accuracy and repetition. They are important factors as rehabilitation treatment without ability to fully improve the ROM of the patients can lead to easy reoccurring of ankle injury[7] .

Several autonomous ARS have been developed by various research groups. There are two main designs of ARS i.e., Wearable-Based and Platform-Based; see Zhang *et al*. [14]. Wearable-Based ARS is a robot that requires patients to attach their legs to the robot and rehabilitate their ankle in the Orthosis (a device that is attached to the body to manipulate the body) or exoskeleton. Platform-Based ARS is a device to manipulate patients' feet by placing their feet on the platform which will be actuated by the device [44].

3.1 Platform-based ARS

A Platform-based ARS uses end effectors in the form of Stewart Platform. Additionally, the robot has ability to facilitate motion therapy and muscles strength training [45]. Examples of Platform-based ARS are Rutgers Ankle, 3RSS/S (Rotational-Spherical-Spherical) Ankle Parallel Robot, and 4-DOF mechanism with two platform ankle robot. In terms of rehabilitating ankle sprain injury purposes, the last two robots will be chosen as examples of platform-based ARS in this review.

3.1.1 Rutgers Ankle

Rutgers Ankle is a pneumatically actuated 6 DOF Stewart platform designed by M.Girone *et al*. in 2002 (shown in Figure 4) [41, 46]. The device was aimed at allowing patients to carry out rehabilitation through a Virtual Reality (VR) environment, using the Stewart platform as a haptic interface. Apart from sprained ankle rehabilitation, the Rutgers Ankle was also used in clinical trials for motor training for stroke survivors [47]. In addition, this design applied 6 double acting pneumatic cylinders and controlled by on/off solenoid valves. It can move and supply forces and torques in 6 DOF as required by ankle rehabilitation scenarios [46]. In 2004, Boain *et al.* developed dual Stewart platform mobility simulator consisting of two Rutgers Ankles, which improved the condition of post-stroke rehabilitation by improving gait of the patients [48].

The advantages of using pneumatic actuators are high power-to-weight ratio, ease of maintenance and cleanliness. Despite its advantages, Rutgers ankle's pneumatic drives need a compressor for air flow inside the pneumatic system which is big and heavy. This hinders the portability of Rutgers ankle to use at home.

Figure 4 Rutgers ankle

3.1.2 3RSS/S (Rotational-Spherical-Spherical) Ankle Parallel Robot

The 3 RSS/S ankle parallel robot consists of a moving base connected to 3 fixed linear electrical actuators by 3 corresponding fixed length floating arms by means of spherical joint (shown in Figure 5). The robot was developed by F. Patane *et al.* in 2006 [42]. It uses electrical actuator instead of pneumatic actuator, which is good in terms of portability. The electrical actuators do not require a compressor which is used by pneumatic system [49]. The limitation of this robot is its inability to relocate its axes of rotation [42]. The original scheme of the robot should be redesigned to increase the number of DOF so that the robot can be more flexible [42].

However, in terms of control it is difficult to do a lot of kinematics calculations of the machines due to the increasing number of DOF [50, 51]. This can hinder the accuracy of rehabilitation exercise to ensure proper recovery of the ankle. The complexity of ankle kinematics in dynamic modelling can cause difficulty to simulate the ankle complex motion during offline programming. To overcome the problem, Sun *et al.* had proposed teaching and playback control system for ARS that could help to solve these problems [52].

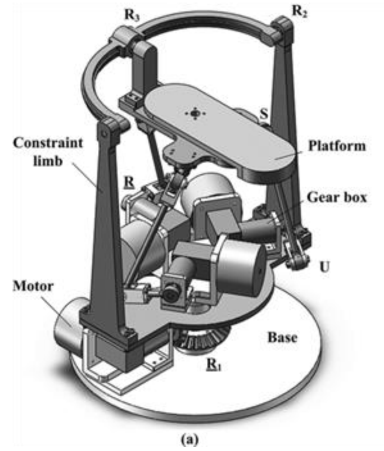


Figure 5 3RSS/S (Rotational-Spherical-Spherical) Ankle parallel robot

3.1.3 4-DOF MKechanism with Two Platform Ankle Robot

An ankle rehabilitation platform with 4 DOF consists of 2 upper platforms and 3 limbs driven by 4 pneumatic actuators (as shown in Figure 6). This robot was designed by Yoon *et al.* [43]. It has additional features to allow ankle and foot motions including toe and heel rising. In addition, it allows conventional ankle rotations as the mechanism can generate relative rotation between the fore and rear platforms as well as pitch and roll motions [43]. Due to the reconfigurable nature of the platform, this device can be used for ROM, muscle strengthening and proprioceptive exercises required in the ankle rehabilitation program [42, 53]. With additional DOF, the device anticipated to be more flexible in application and has wide range of exercises for ankle rehabilitation treatment[52].

However, this design is not portable since it uses hydraulic and pneumatic technologies, which seems to be unsuitable for domestic environment especially at home. Pneumatic system requires additional devices such as compressor to implement the system. Although additional features give greater flexibility to the robot, the modelling and kinematic calculation will be more complicated [50]. However, this problem can be fixed using teaching and playback method introduced by Sun *et al.*

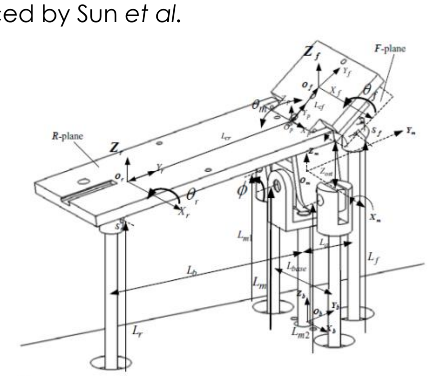


Figure 6 4-DOF mechanism with two platform ankle robot

3.2 Wearable-based ARS

Wearable-based ARS is a robot that takes the form of Exoskeleton or Orthosis. It has 3 major types; they are Extenders, Orthotic, and Prosthetics [44]. In addition, it is used as a remedy for foot drop where the braces are moulded to fit the patient's foot to prevent foot drop [45]. Examples of these robots are Anklebot, Reconfigurable Robot (developed by Satici *et al.*), and Ankle Training with robotic device (from Forrester *et al*.). From all wearable based ARS, only Adaptive Wearable Robot is built based on ankle sprain rehabilitation purposes.

3.2.1 Adaptive Wearable Parallel Robot

Adaptive Wearable Parallel Robot is a 3 DOF, wearable-based pneumatic driven ankle rehabilitation robot designed by Jamwal *et al.* in 2011 (shown in Figure 7) [54]. The actuators of the robot are placed parallel to the shinbone. It consists of 2 parallel platforms which represent a "U" shaped top platform for leg support and a moving platform at the bottom to actuate foot and ankle of the patients. This is important as shinbone is unaltered during treatment. In addition, the robot is compatible with the ankle motions as it uses pneumatic muscle actuators (PMA) which is also light in weight. Kinematic compatibility of the design can be achieved using flexible cables along with PMA [54]. Generally, most of wearable-based ankle rehabilitation robots are specific in terms of improving gait of stroke patients due to foot drop [54].

Apart from lighter, PMA also provides greater power-to-weight ratio compared to electromagnetic actuators and also has low impedance which allows back drivability [54]. The system still requires external equipment such as air compressor which hinders the portability of the robot. Another disadvantage is the pneumatic actuator is unable to provide resistance exercise which is critical for muscle strengthening.

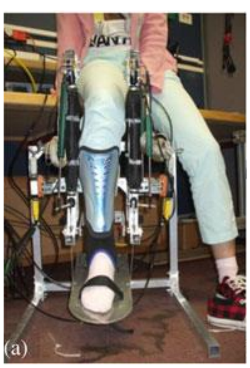


Figure 7 Adaptive Wearable Parallel Robot for Ankle Rehabilitation

3.3 Discussion on Robot-aid ARS

Overall, both Platform-based and Wearable-Based ARS have their roles in helping ankle recovery of patient. Basically, platform-based ARS is helping patients to recover from ankle sprained by improving muscle strength and ROM of the patients. Meanwhile, wearable-based ARS is suitable for stroke patients during stroke or post-stroke to improve gait although wearable-based ARS can be used for ankle sprain [45, 55]. However, not all platform-based ARS and wearable-based ARS can fulfil all exercises; i.e., they are not suitable for balancing exercises whereas for platform-based, this device is less effective in improving ROM of the ankle because of restricted workspace [41], [54].

Amongst all reviewed robot-aids ARS, Adaptive Wearable Parallel Robot is the best of robot-aids ARS in terms of giving the suitable exercises for ankle sprain treatments. Not only this robot is usually aimed for stroke ankle rehabilitation; but also it provides unique features (high payload and stiffness) required for ankle sprain rehabilitation.

4.0 NON-VISUAL BASED ARS

A non-visual based ARS works using non-visual sensors attached to the ankle and foot to collect information about movement. Their sensors are commonly classified as inertial, magnetic, resistance and some others. In a rehabilitative course, the sensor must be localised on limbs of a patient so that undesirable patterns can be corrected.

4.1 Inertial Based Sensor ARS

Inertial based sensor ARS such as accelerometers and gyroscopes are shown in Figure 8. Inertial based sensor has been frequently used in navigation and augmented reality modelling [56-60]. This kind of sensor is beneficially comprehensible and cost-efficient way for human motion detection. The motion data of the inertial sensors can be transmitted wirelessly to a work base for further process or visualisation. Inertial sensors have high sensitivity and large capture areas. However, its limitation is the position and angle of an inertial sensor cannot be correctly determined due to the fluctuation of offsets, and measurement noise, leading to integration drift. Therefore, designing drift-free inertial systems is the main target of the current research.

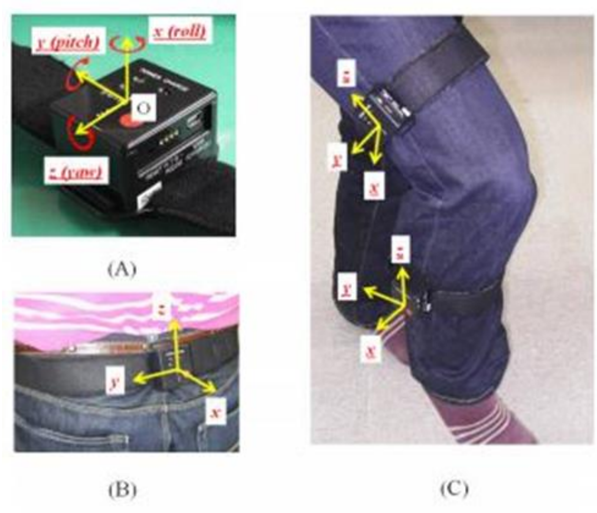


Figure 8 Inertial based sensor system for ankle rehabilitation system. (A) Outer appearance of (Inertial Measurement Unit) IMU sensor; (B) Angular velocities and acceleration are obtained around each axis; (C) Location of IMU sensors to be attached with a subject

4.2 Magnetic Sensor Based ARS

Magnetic sensor based ARS have been widely used for tracking user movements in VR due to their size, high sampling rate, lack of occlusion, and etc. Despite its contributing great successes, magnetic trackers have inherent weaknesses, such as latency and jitter[60]. Latency arises due to the asynchronous nature by which sensor measurements are conducted. Jitter appears in the presence of ferrous or electronic devices in the surrounding, and noise in the measurements. The latency arises of magnetic based sensor will cause time delay and effect of some physical change in system being observed. A number of research projects have been launched to tackle these problems, using Kalman filtering or other predictive filtering methods [16, 61–63].

4.3 Resistance Based Sensor ARS

Resistance sensors such as bend sensors and force sensors have been regularly used in ROM and angulation force measurement. Ankle sleeve with bend sensors have been embedded on the lateral and anterior sides of the foot and ankle is shown in the Figure 9. This sensor can provide accurate angular information and torque measurement. However, the placement of the sensors could limit the motion apparent on the side of ankle [4].

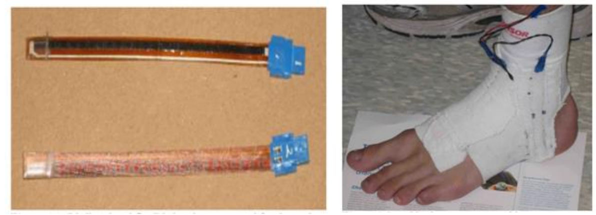
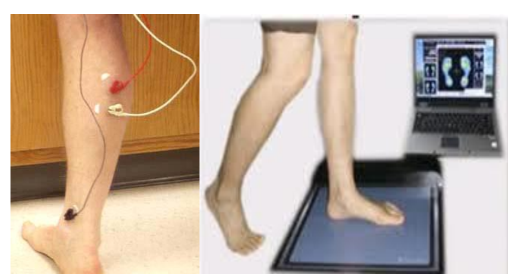


Figure 9 Resistance based sensor ARS (a) Bi-directional Flexible bend sensors used for the project; (b) Ankle sleeve prototype with sensors embedded on the lateral and anterior sides

4.4 Others Based Sensor Techniques

The electromyogram (EMG) is an analysis of the electrical activity of the contracting muscles depicted in Figure 10. It is often used to detect whether the muscles are working or not, and to determine the sequence of the working of the muscles to respond the movements. EMG can also provide an amount of intensity of muscle activity. This technique has commonly been used in rehabilitation exercises. Research in EMG is flourishing; a lot of researchers are finding applications of EMG bio-signals, see [64–66]. However, EMG is unable to record the inner muscle activities. In between, ankle sprain rehabilitation exercises involve a lot of the inner muscle linked to the ankle tendons. Thus, EMG is not suitable for ankle sprain rehabilitation system. Misallocation of EMG sensor at the interest area is also one of the disadvantages of using EMG in ankle sprain treatment.



(a) (b)

Figure 10 Others based sensor of ARS (a) Electromyogram (EMG); (b) Foot Scanner

The Foot scan system is a matrix of resistive sensors combined with patented electronic technologies shown in Figure 10(b). This system involves in measuring high speed dynamic movements, footprint and foot area, gait-line, pressure/time curve (pressure measurement), in-toeing and out-toeing angles, amount of heel pressure, duration of heel contact, pronation or supination, and impulse. Foot scanner has a 6 DOF movable support surface, allowing the investigation of the effect of moving support surface on the athlete. It has advantages for clinical use such as repeatability, validity, reliability and resolution, ease of use, and easy to synchronize with software.

Disadvantages for this system are multiple steps cannot be collected and no measurement possibility between foot and insole itself.

In the upper limb application a glove-based devices for analysis of hand gestures is developed [67-70]. These devices adopt sensors attached to a glove that transduces finer flexion and abduction into electrical signals, to determine hand pose [30]. This idea can be applied in ankle rehabilitation application. Hence, the socks-based device for analysis of foot motion can be implemented. The Socks-based adopt sensors to attach with socks that identify finer flexion of the toes and Inversion/Eversion of ankle joint motion.

4.5 Discussion on the Non-visual ARS

Naturally, different type of based sensor gives different advantages for ankle sprain rehabilitation. However, these sensor types can be combined for better ankle sprain rehabilitation application. In the inertial based sensor, 3D angle measurement requires the additional of a second reference axis. Thus, a number of 3D segment orientation measurement techniques have been developed by incorporate magnetic based sensors into inertial based sensor (compliment kinematic sensor) using the magnetic field vector as a second reference axis. Veltink *et al*. [71] have successfully developed a 3D technique for monitoring foot orientation during walking by using the direction of progression as a second reference axis. This development is also known as X Sens. It is a well-developed sensor system with combination of inertial based and magnetic based technologies [72] shown in Figure 11. However, this technique is limited only to be used during ambulation.

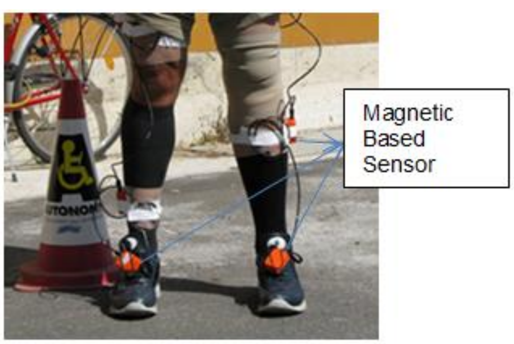


Figure 11 Magnetic based sensor (X-Sens Sensor) attached at the foot and ankle

Resistance-based bend sensors are used in bi-directional in which the resistance changes during the sensor bend. This sensor can provide direction y-y axis, but it is unable to provide direction in plane. Thus, Bend-based (resistance) sensor is combined with an accelerometer (Inertial-magnetic based sensor) to determine where the ankle is bending and to study ankle angle measurement. Thus, this combination will provide the good ARS for ankle sprain. However, non-visual based sensors are not appropriate for home application ARS due to misallocation of clinical sensor and obstruction towards ankle motion. Fortunately, these problems can be overcome by Visual based ARS.

5.0 VISUAL BASED ARS

Visual based ARS is to provide an accurate position estimation of human ankle movement over time using an optical sensor. Visual based ARS is classified either visual marker based or visual marker-free based, regarding on the placement markers on human ankle.

Visual marker-based ARS is a technique that uses optical sensors, i.e. cameras, to track human movements, which are captured by placing markers on the human body. As human skeleton is a highly articulated structure; twists and rotations make the movement fully in 3D [36]. This technique can be applied for ankle motion tracking, where the markers are placed on the ankle joint and toes. The camera captures the rotations of movement to project foot and ankle anatomy under 3D perspective.

However, there are a number of disadvantages of the visual marker-based ARS. The main disadvantage is the usage of markers. The markers are influenced by illumination condition, resulting that the system is only limited to the controlled and calibrated environment. This marker based system is prone to errors due to occlusions, detection noise, and the proximity between markers. Furthermore, the markers placements at human joints are often obstructive and cause unnatural motion to the subject which can contributes to injury. The unnatural motion is amplified when the subject is involved in repetitive and fast-paced motion. The marker-based ARS are also restricted to limited DOF because mounted markers make them difficult to provide accurate sense joint rotation. This leads to the infeasibility of representing a real 3D model for the sensed objects [73]. Thus the markers often limit the capability of rehabilitation system. A visual marker-free based system must have less restrictive motion capture technique and is capable of overcoming mutual occlusion problem.

The visual marker-free based ARS is a technique for human body kinematics estimation that does not require markers or fixtures placed on the body which greatly enhances the application of human ankle motion capture. To date, marker-free based systems are capable of overcoming the mutual occlusion problem as they are mainly concerned with the boundaries or features of foot and ankle [30]. These foot and ankle features such as colour, shape and depth distance are recorded by the visual marker-free based ARS, which act as various types of input data. These data will provide a lot of information and advantages for motion analysis such as reducing processing time, producing accurate accuracy, and producing wide range of 3D reconstruction view.

The drawback of a visual marker-free ARS is its inability to provide an effective feedback and patient motivation. Combining it with VR offers many advantages such as increasing the patient motivation, allowing repetitiveness of learning trials, providing possibility to tailor treatment to individual subject and delivering safety into the environment. Previous researchers had applied various VR technologies in rehabilitation systems using this model. Since the model is out of this scope, interested readers can refer to [74-79]. A new development rehabilitation tools based on VR has attracted significant interest in the physical therapy arena [74]. Thus, the VR technology can be used to collect the lower limb (ankle and foot) motion tasks to provide pervasive accessibility to enable patients to take rehabilitation treatment in clinic and at home.

Moreover, an inference system with VR technology has been suggested for ankle rehabilitation to provide a Virtual Environment (VE). In this system the patient's ankle joints, metatarsal joints and foot avatars interact with some virtual objects in order to perform different (inversion/eversion, dorsiflexion/plantar flexion) actions. This VE can be supported by Kinect camera [80] motion sensing devices (developed by Microsoft), which are used for tracking patient ankle joints and foot movements.

6.0 DISCUSSION

Ideally, an ARS is to guide ankle sprain patient in rehabilitation exercises and identify the improvement level of the ankle sprain patient. The ideal ARS is based on the identification need, which includes *user-friendly, performance efficiency, validity and cost*. The user friendly ARS is to provide a safe environment during rehab exercise without electrical shock, injuries to patient, to provide therapy media feedback based on the progress of the patient motion, to offer semi-portable in usage, and home applicable. The best performance efficiency is to stipulate the freedom of ankle movement during exercises, to provide large data storage for patient daily rehab exercise, to provide semi-automatic or full-automatic without therapist supervision, and easy system upgrades for processing time. The best validity of ARS to the clinical treatment is to provide accurate in ankle motion measurement (position, angle, and velocity) and to provide repetition exercise based on the patient progress. Maintenance cost and market value for ARS must be inexpensive and affordable for most users.

Each type of ARS has its own speciality, strength, weakness, potential, and treat. Thus, critical analysis among Robot-aid ARS, Non-visual ARS and Visual ARS based on the need identification are presented in Table 1 to identify the most suitable ARS for the ankle sprain patients. The analysis shows that visual based marker-less ankle rehabilitation is the best ARS for home application. This system is more user friendly compared others ARS because it is portable, provides automatic visual media feedback and safe with assessment protocol and without skin contact sensor which may cause injuries. Performance of the visual Marker-less based ARS is efficient, which provides full ROM, large data storage and provides easy software system upgrades. This system is 90% validity as the doctor's assessment due to its able to provide 90% similarity result by experienced specialists when using goniometer. The repeatability use of system will provide precise and accurate result on the ROM ankle measurement. This system also yields the cheapest cost compared to others. As a result, this visual marker-less based ARS system is the most suitable for ankle rehabilitation therapy at home.

Table 1 Critical analysis between Clinical ARS, Robot-aid ARS, Non-visual ARS and Visual ARS

	Clinical ARS	**Robot-aid ARS**	**Non-Visual ARS**	**Visual ARS**
Example System	Rehabilitation using rubber band and wobble board	Wearable Based (Adaptive Wearable Parallel Robot)	Combination Bend sensor with inertial-magnetic sensor	Visual Marker-free Based (Kinect Camera)
User-Friendly				
Media Feedback	- Patients need to attend rehab to acquire feedbacks from therapist. - Diagnosis feedback from therapist is hard as state of recovery is determined by sight.	- Therapist can help to set the robot configuration to give suitable treatment for patients according to his/her evaluation [41].	- Does not provide media feedback.	- Provide automatic classification (normal, mild, moderate, severe ROM) media feedback such as the ankle position and angle motion value in visual display[81].
Safety	- Safe as along as treatment is monitored and supervised by therapist manually.	- Direct contact with patient and able to inflict physical injuries if the system is malfunctioning. - To increase the safety of equipment, by using sensors or limit switches.	- Direct contact with patient. - Will cause obstructions to ankle during rehab exercises - May cause injuries if malfunctioned.	- Have protocol therapy and assessment criteria on the rehab level. -Without skin contact and in-vitro to patient so no cause injuries

	Clinical ARS	Robot-aid ARS	Non-Visual ARS	Visual ARS
Semi-portable	Rubber band and Wobble Board are semi-portable.	Depends on the design, i.e. Anklebot requires external air compressor to actuate [82]. This system is not portable and heavier than visual and non-visual ARS.	- Semi-portable - Sensors are small in size. Examples: - Dimension of Bend Sensor is 114.30x6.35x0.51mm.	- Kinect Camera and computer are portable for usage.
Home application	- No suitable for home application due to lack of proper guidance from therapist	- Depends on the design of the robot. Most of the robot is hard to relocate from one place to another due to a certain factor such as weight and assembly.	- Misallocated of the sensor at the patient during home application if the sensor placements are done incorrectly.	- Instruction and step of exercise is provided during rehab exercise, patient movement can be tracked and data from the treatment is recorded automatically.
Performance Efficiency				
Freedom of movement	- The treatment is structurally, DOF is unlimited.	- DOFs of patients are constrained due to the limitation of system. - Most of the robots are designed to operate beyond the ROM of human ankle.	- Less limitation of movement.	- No limitation of movement, thus most of the ankle full ROM can be measured and recorded.
Semi-automatic	- Manually rehab exercise by patients and monitored by therapist.	- Semi-automatic or fully automatic especially in dealing with repetition. - Supervision from the therapist is still required.	- Manually self-attached sensor on patient. - Record graphical data automatically.	- Semi-automatic, no needs monitoring. - But patients still have to follow instruction from the system.
Data Storage	- Does not have proper daily exercise data storage because patient can do the exercises manually and some-times recorded by therapist.	- The system can record the progress of rehabilitation exercise although the robot can't determine the actual state of recovery which is depended by vision.	- Data acquisition rate is 1000 sample per second. - Information is displayed to allow therapist for monitoring patient's database on a graph. - Ability to save, review and place comparative data.	- Large data storage based on hard disk size. - Information is displayed; therapist can scan through patient's daily databases. - Ability to save, review and place comparative data.
System Upgrades	- Manually rehab exercises; exercises can be upgraded based on the patient progress.	- Difficult implementing system upgrades while compared to visual or non-visual ARS.	- Difficult for sensor upgrading but easily upgrades in software.	- Easily upgrades in system software such as the programming upgrades.
Validity				
Accuracy	-Need the experience and observation of therapist, making it inaccurate due to inconsistency from the therapist. -Measurement angle by using goniometer.	- The system is accurate if feedback or closed loop system is implemented into the system such as sensors. - Can accurately display distance, position, velocity, angle using accelerometer in foot platform.	- The system is accurate based on usage of the sensor such as: - The X-sens (MTI-G Technical specification): - Static accuracy (roll/pitch) <0.5° - Static accuracy (heading) <1° - Dynamic range: Pitch ± 90°; Roll/Heading ± 180°	- Able to display the visual marker as correctly on the foot. - Accurately to display distance position, velocity. - Able to provide angle measurement which similar than goniometer [83].
Repetition	- Patient can repeat doing rehabilitation exercises with his/her own strength	- This system has ability to perform the passive exercises over and over again without effort from the patients	- Non-vision ARS which requires patients to repeat the exercises by themselves.	- Patients do active motion exercises repeated based on the guideline of system.
Cost				
Maintenance cost	- Depend on the usage of rehabilitation equipment.	- High maintenance cost due to the sophisticated feature of robot. - Sensors are needed for tuning to ensure the accuracy of the machine. - Robot mechanism is exposed to wear and tear.	- Maintenance cost is slightly expensive than visual system due to the sensor is sealed chipset.	- Maintenance cost for this is cheaper due to easy system update.
Market value	- One hour rehab treatment with therapist is around	- The system is expensive due to the cost of materials that are used to manufacture the	- Price of non-visual based ARS is around RM8,000 ~ RM10,000.	- Cheaper cost - Kinect camera is RM500 per unit.

	Clinical ARS	Robot-aid ARS	Non-Visual ARS	Visual ARS
	RM200. - Attend at least 10 times per month before recovery.	robot. - Price is around RM 10,000 ~ RM15,000.		- Connected to laptop (RM2000) - Total price is around RM2500

7.0 CONCLUSION

This paper reviewed the development of technology ARS in term of criteria of each type of ARS such as robot-aid, non-visual based, visual marker based, and visual marker-free based. This paper highlighted that a successful designed ARS was to accommodate all factors, such as user friendly, operation performance efficiency, validity and reasonable cost. The strength, weakness, potential and threat of the technological ARS were reviewed clearly and comprehensively in this paper.

From the overall review on ARS, the most suitable home application ARS for patients is visual marker-free based ARS, justifying the relevancy and significance of the ARS. This visual marker-free based ARS is user friendly (by given user interface) and media feedback, good efficient in performance (by given big data storage for data ROM, acceleration and speed), validity (by given accurate and precise data for repeatedly use) and inexpensive in cost. From the reviewed criteria, the strength and weakness of ARS could be identified. Researcher can enhance the strengths of ARS and overcome its weaknesses for the further development. In this review, the potential and threat of ARS needed to be considered as important development features in the future.

Hence, proposed projects in the future should cope with this technical issue by attempting to grasp human foot and ankle joint motion at each moment. Achieving such an accurate localization of the foot and ankle joint may lead to more efficient, convenient and easier kinetic and kinematic modelling for movement analysis.

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