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DESIGN OF AN ANKLE REHAB ROBOT WITH A COMPLIANT PARALLEL KINEMATIC MECHANISM

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ABSTRACT

In this paper, we present the design of a novel ankle rehabilitation robot (ARR), called the Flex-ARR, that employs a compliant parallel kinematic mechanism (PKM) with decoupled degrees of freedom. The Flex-ARR is designed to collocate the biological center of rotation of the ankle with that of the robot's center of rotation to allow natural ankle motion. While multiple ARR designs have been developed in research labs and some are commercially available, their clinical adoption has been limited because they do not emulate the natural motion of the ankle. The Flex-ARR leverages a unique PKM design that uses compliance to absorb minor misalignments between the center of rotation of the ankle and the robot, thereby allowing natural ankle motion. Also, because of its unique design, the PKM inherently accommodates variations in user foot sizes with minimal adjustments. The Flex-ARR is designed to provide multiple training modes that allow for both rehabilitation and assessment modalities. This paper provides a review of the literature to identify the key factors that have limited the clinical adoption of existing ARRs. Based on this, functional requirements and design specifications for an optimal ARR are defined. This is then used to develop a design strategy, followed by conceptual and detailed design.

1. BACKGROUND AND MOTIVATION

The ankle is a complex joint connecting the leg region of the lower limb to the foot, and allows for daily activities like maintaining balance and walking [1,2]. The portion of the lower limb between the knee and the ankle is commonly referred to as the leg region, while the portion below the ankle is the foot. Fig. 1 shows the ankle and foot with its associated axes, planes, and motions. The three motions at the ankle are plantarflexion/ dorsiflexion (PF/DF) in the sagittal plane about the pitch axis, inversion/eversion (INV/EV) in the frontal plane about the roll axis, and abduction/adduction in the transverse plane about the yaw axis. The ankle can support very large loads (~ 3 to 6 kN) during simple activities like walking. Not surprisingly, it is the

site of many musculoskeletal injuries that require rehabilitation such as sprain injuries and ligament injuries, with over twenty-three thousand cases of ankle sprains occurring per day in the USA alone [2]. In addition to musculoskeletal injuries, the ankle also requires rehabilitation in cases of neurological disorders/injuries such as cerebral palsy and stroke where there has been loss of motor control or the patient has a drop foot [3,4]. Physical therapy plays a vital role in the treatment of said injuries, and studies have shown that without this therapy, about half the patients experience future problems [2].
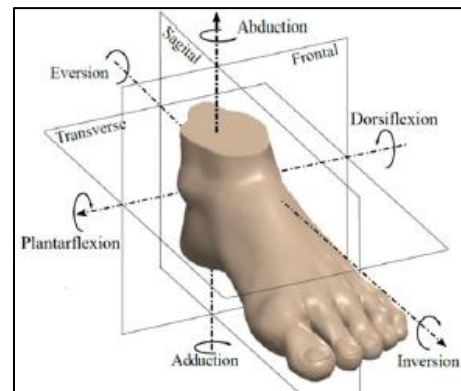

Fig. 1 Ankle axes, planes and motions [5]

Typically, rehab for musculoskeletal ankle injuries involves an acute phase (within 48 hours of the injury) treatment by immobilization and a sub-acute phase (between 2 days to 2 weeks after injury) treatment that involves passive /active range-of-motion (ROM) and muscle strengthening exercises. Therapists can use manual exercises, free weights, specialized passive devices such as balance boards, resistance bands, etc. to conduct all of the above therapy [6]. Stroke neuro-rehabilitation usually includes task-specific movement training to promote motor recovery – e.g. by using a gait training robot to mimic walking gait of the patient [5]. Across the various forms of therapy mentioned above, therapists find it challenging to conduct exercises in a repetitive and precise manner to ensure

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consistency of treatment e.g. during manual exercises a therapist often rely on their skills and experience to conduct the exercises in a highly repetitive manner and they have little objective measurements to give them feedback on their methods. In addition, therapists expend immense energy in conducting the therapy which leads to fatigue and can potentially impact their quality of treatment. Therapists also need to conduct assessment of the patient's ankle during the course of therapy. They may conduct this assessment using tools such as a goniometer (to assess range of motion) or dynamometer (to assess muscle strength), and they often use their own subjective judgement to conduct such evaluation [7–11]. For effective rehab, in addition to repetitive (i.e. dosage) and precise (i.e. consistent) exercises, there remains a need for assessment tools that provide accurate, objective, and quantitative information on the health of the ankle.

Robotic devices for rehabilitation have been proposed to address these challenges, since they have the following purported advantages: (a) robots can be designed to provide a wide range of therapy exercises in a highly repetitive and consistent manner, (b) robots can employ multiple sensors to capture accurate quantitative data about the ankle which can be used to provide objective assessment and therapy decisions, and (c) robots are able to deliver high-dosage and high-intensity therapy without tiring the therapist [2,7,12–14]. While several robots have been proposed for ankle rehabilitation, the literature recognized the following technical challenges in the design and performance of ankle rehabilitation robots (ARR) [7,15]:

(1) **The mechanism architectures of existing ARRs do not adequately emulate the natural motion of the ankle**, i.e. allow the patient to move their ankle as they naturally would. In literature it's been proposed that misalignment between the robot's center of rotation (R-COR) and the biological center of rotation (B-COR) is responsible for preventing the natural motion of the ankle [7,15,16]. In addition to unnatural motion of the ankle, negative consequences of misalignment include reaction torques at the ankle or unnatural compensatory motion of the patients lower limb which interferes with the therapy [15,17]. Another deficiency was recognized through the survey of literature – ARRs discussed in the literature are unable to absorb minor misalignments of the CORs due to their rigid and highly stiff mechanisms.

(2) **An inability of ARR to adapt to the highly varying individual needs of the patients** who present with large variations in the size and shape of their lower limb. This variation also includes varying range of motion (ROM), muscle strength, axis and center of rotation and make the set and use of the ARR by a physical therapist more onerous.

In this paper, we present the design of a novel ARR, called the Flex-ARR (Fig. 2), which uses a compliant parallel kinematic mechanism (PKM) to provide two degrees of freedom (DOF) – PF/DF and INV/EV rotations of the ankle. This compliant PKM has been previously used in the design of a laparoscopic surgical instrument to collocate the user's wrist with the center of rotation of the surgical instrument's input articulation joint [18,19]. A similar PKM is used in the Flex-ARR to decouple the two rotational DOF (PF/DF and INV/EV) such that they can be independently actuated and controlled. In addition, the compliant PKM (unlike other ARRs in the literature which typically use rigid mechanisms) allows the Flex-ARR to inherently accommodate for variations in patient's lower limb dimensions without the need for onerous adjustment features. The compliance also allows the mechanism to slightly deform to absorb minor misalignment of the B-COR and R-COR and allow for natural ankle motion. Furthermore to streamline the workflow, the Flex-ARR uses a novel pre-therapy alignment tool that ensures that the biological center of rotation (B-COR) and the robot's center of rotation (R-COR) are collocated when the patient interfaces with the Flex-ARR. Based on the published literature and conversations with physical therapists, all existing ARRs rely on visual alignment (i.e. eye-balling) of B-COR and R-COR without the use of any intentionally designed alignment tools or aids, which can prove to be challenging for the therapist. The novel alignment tool presented here allows the therapist to locate the B-COR while the patient is seated or laying down on an examination bed, prior to strapping the patient to the Flex-ARR thereby allowing better view and access.

The Flex-ARR is designed to provide multiple modalities such as continuous passive motion, & muscle strengthening, and assessment modes that assess ROM, proprioception, & isokinetic muscle strength. The compliance of the PKM is both beneficial in absorbing the misalignment of CORs, but poses the challenge of position error due to deformation of transmission elements under loading. In the Flex-ARR design, we optimize the compliance of the PKM such that it is stiff enough to limit deformations and resulting position errors, while being compliant enough to absorb misalignment of the B-COR & R-COR to ensure natural ankle motion without discomfort.
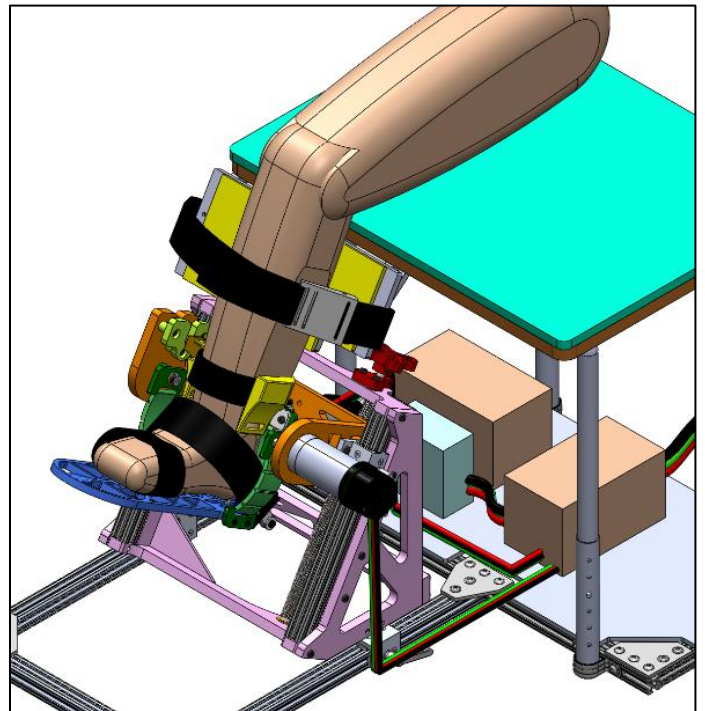

Fig. 2 Flex-ARR Concept Full System CAD

The rest of this paper is organized as follows. A detailed review of ARRs in the literature is presented in Section 2. Through analysis of current ARRs limitations, ankle biomechanics, and assessment of therapist needs through expert interviews, a list of functional requirements and design specifications are compiled in Section 3. A design strategy to address these requirements and specifications and resulting and concept generation is presented in Sections 4 and 5, respectively. The detailed design of the Flex-ARR is covered in Section 6, followed by future work in Section 7.

2. PRIOR ART ON COMMERCIAL & RESEARCH ARR

ARRs can be categorized into two functional types as outlined in several review papers: wearable and platform [20–22]. Wearable ARRs such as exoskeletons for rehab [23] comprise a customizable anthropomorphic user interface for reinforcement and corrective training procedures [8,20,21]. Platform ARRs comprise a mobile plate that transmits motion to the patient's foot and is connected to a static base [20,24] via some mechanism. Platform ARRs are most commonly used in clinical settings (physical therapist clinic), and are typically designed to control the INV/EV and PF/DF motion of the ankle [20,21]. They are used in rehab to improve the ROM of the ankle, avoid ankle stiffness, and improve muscle strength. Wearable ARRs are typically used in gait training, balance training, & in specialized functional therapy such as sports rehab. Hence, each type of ARR serves a specific purpose in rehabilitation [20,21]. The scope of this literature review includes platform-type ARRs in research and commercial devices. Table 1 and the associated Fig. 3 provides a summary of various platform-based ARRs developed in research. This research and design effort is focused on platform ARRs as they remain an unsolved challenge in the field of rehab robots, and meet a wider range of needs for the therapist. Also, platform ARRs do not impose additional constraints such as being light weight which apply to wearable ARRs as they are typically 'worn' by the patient (e.g. like an exoskeleton).

Typically, platform ARRs implement PKMs [7,21,22] between the mobile plate and the static base as opposed to serial kinematic mechanisms due to the former's multi-DOF capability in a compact form factor, and high stiffness [25]. However, most PKMs in existing ARRs present kinematic or accessibility limitations in their ability to align their R-COR with the B-COR of the patient's ankle. These ARRs either have R-CORs that do not remain stationary [26–28] or have R-CORs that are fixed but present challenges in being able to adjust their R-COR to collocate it with varying B-CORs of different patients [16,29]. Few ARRs such as the modified agile eye [16] and the serial gimbal inspired design [29] proposed in research attempt to tackle the issue of COR collocation by relying on a visual alignment – that is the therapist first uses their skill and judgement to visually determine the B-COR of the patient, and then second, they attempt to collocate it with the R-COR of the ARR. This process has the potential for error in both steps – research has shown that when medical experts attempt to identify the B-COR using sight, the error in their estimation can be as

high as 9mm [30]. This error is compounded by the second step, and there is no data available on the error involved in visually aligning a point on the patient's ankle with the R-COR of the ARR. Recognizing these limitations, others have used surface electromyography to track unfavorable muscle activation to identify misalignment [31]. The survey of the literature also highlighted additional requirements such as ensuring user compatibility, comfort, and safety during the use of the ARR [14,24,32,33].
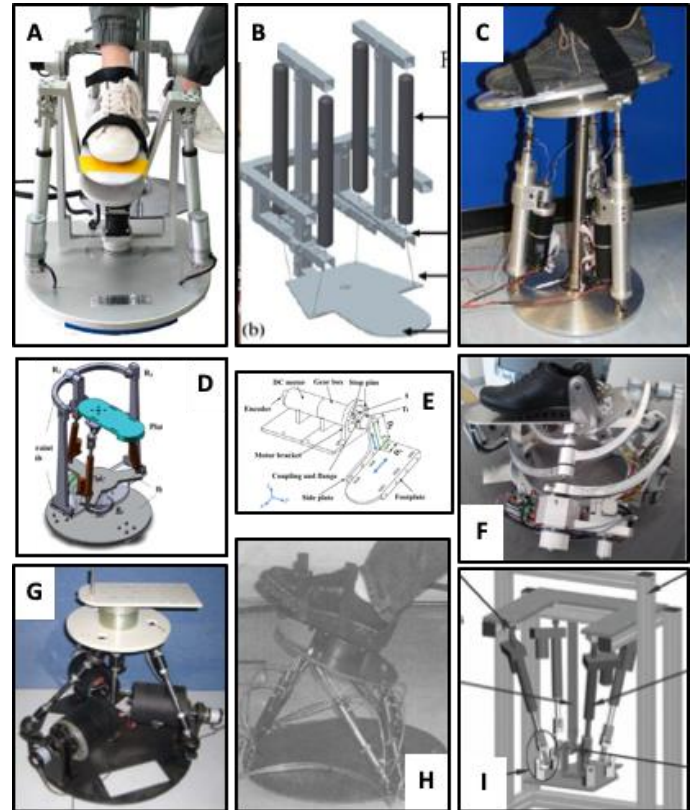

Fig. 3 Images (A) to (I) ARRs investigated. (A) PARR [25], (B) PMA based ARR [15], (C)[14], (D)[29], (E) Proprioception ARR [34], (F) Modified Agile eye ARR [16], (G) [35], (H) Stewart Platform derivative [26], (I) [36]

The Rutgers Ankle (Fig. 3 H), one of the first developed ARRs, employs a 6 – UPU (U is a universal joint, P is a prismatic joint) Gough-Stewart platform inspired PKM [20]. The Rutgers Ankle provides six DOFs [26]. The translational DOFs are only used for advanced training protocols such as gait training. Additionally, the design of the Rutgers Ankle, along with many similar platform ARRs make it difficult to collocate the R-COR with the B-COR – the R-COR is in constant motion and attempts to collocate it with the B-COR limit the ROM and increase control complexity [14,35,37]. Similar to the above Rutgers ankle design, a 3-UPS/U (S is spherical joint, and /U is an additional pillar with a universal joint) PKM based ARR (Fig. 3 C) was developed, which provides the PF/DF and INV/EV motions with redundant actuation [14]. The redundancy in the robot actuation serves to eliminate singularities and improve dexterity. This ARR uses a central strut fixed to the base plate

Table 1. Selection of Key ARRs investigated in the state-of-the-art review of the ARR research literature

Author (Robot Name)	Year	DOF	Robot ROM (deg)		Type of Training
			PF/DF	INV/EV	
Zhang et. al. [25] (PARR)	2019	3	42/26	16/16	Continuous passive motion, assistive, resistance
Kumar et. al. [32]	2019	6	37/20	35/15	-
Zhou et. al. [38]	2015	1	-	-	Proprioceptive evaluation
Jamwal et. al. [15]	2014	3	46/46	26/26	Continuous passive motion, resistance
Saglia et. al. [14] (ARBOT)	2009, 2013	2	15-20	-	Continuous passive motion, assistive, resistance
Wang et. al. [39]	2013	3	50/50	30/30	-
Malosio et. al. [40] (PKAnkle)	2012	3	-	-	Continuous passive motion
Yoon and Ryu [33]	2005	4	50/50	55/55	Continuous passive motion , resistance, balance
Girone et. al. [24] (Rutgers Ankle)	2001	6	45/45	40/40	Continuous passive motion, resistance

and with a universal joint connection to the foot plate. This limits the PKM to two rotational DOF. However, the introduction of the central strut locates the R-COR at the universal joint at the upper end of the central strut, eliminating any possibility for alignment with the B-COR. Other ARRs [35] have proposed similar designs (Fig. 3 G) with the same limitations as discussed above. Other platform-based ARR designs [39][41] attempt to collocate the R-COR with the B-COR by using an RRR (3 revolute joints in serial) chain (Fig. 3 A & D) which surrounds the ankle and locates the R-COR at the intersection of the three rotational axes. One ARR introduces a similar RRR chain to envelope the ankle and uses compliant pneumatic muscle actuators [15]. The ARR shown in (Fig. 3 F) also constrains the R-COR of the mobile platform by adapting a well-known spherical PKM ("Agile Eye"), whose R-COR lies at the intersection of all the revolute joint axes [40]. All four ARRs (Fig. 3 A, B, D, F) discussed above have a fixed R-COR and provide enough space for the patient's foot to be inserted into the ARR. However, as discussed earlier the collocation of the CORs is prone to errors and these ARRs do not inherently absorb these errors to ensure natural ankle motion.

Table 2. Selection of Commercial ARRs investigated

Commercial ARR	DOF	ROM (deg)	
		PF/DF	INV/EV
Kinetec 5090 Club Foot [42]	3	-	-
Kinetec Breva [43]	2	40/30	25/25
Chattanooga – OptiFlex [44]	2	40/60	40/20
BIODEX System 4 Pro [45]	2	30/50	55/40
JACE Ankle A330 CPM [46]	1	40/20	-

Table 2 shows several commercial platform-type ARRs and their key technical specifications. While the weight and overall dimensions of the robots vary, the key performance capabilities of the ARRs include the PF/DF and INV/EV range of motion of the robot. User interfaces are explicitly integrated into all of the commercial ARRs with ergonomic considerations made for lower limb restraint (e.g. straps) and alignment features (e.g. heel stops for the foot) [42–46]. However, they do not address the need of reducing or eliminating the misalignment of the R-COR and B-COR. Few commercial ARRs offer multiple modalities or training modes [43,45]. ARRs such as the Kinetec Breva and the

BIODEX system offer multiple modalities such as Continuous passive motion and muscle strengthening, however they do not include proprioception evaluation. The need for an ARR that allows for natural ankle motion through the alignment of R-COR and B-COR, and that meets the needs of a varying population remains unsolved. Based on the insights gained from the literature review and interactions with therapists, a list of functional requirements for the design of an optimal platform ARR was generated.

3. FUNCTIONAL REQUIREMENTS FOR ARR

Based on the prior art and its analysis presented above and identified needs of therapists and ARRs, the following list of qualitative system level functional requirements (FR) for an optimal platform ARR are proposed:

FR1 – Adequate DOF: The ARR should have adequate DOF for most (if not all) types of therapy and exercises. From the literature, it is clear that any ARR should provide at least two rotational DOF, specifically to allow for motion in PF/DF and INV/EV. The DOF should be actuated to be able to control the user's foot motion in those DOFs. These motions are used in everyday activities such as walking, and hence therapists focus on these motions during therapy.

FR2 – Adapt to Individual Patients (Be Adjustable/ Customizable): The ARR should be able to accommodate the varying needs of patients, due to their varying dimensions of the lower limb or type of injury. The same ARR should be able to accommodate a range of foot sizes, left or right feet, genders, etc. to maximize its utility while requiring minimal adjustments.

FR3 – Natural Ankle Motion: The ARR should provide no kinematic or accessibility limitation to the natural motion of the patient's ankle. Through the investigation for this paper, it's determined that to promote natural ankle motion the ARR should reduce or eliminate the misalignment (lateral and angular) between the B-COR and R-COR. In other words, the B-COR and R-COR should be collocated. While some ARRs in research have attempted to meet this requirement, an effective solution has not been proposed.

FR4 – Multiple Therapy Modes: The ARR should provide multiple therapy modes such as Continuous Passive Motion and Muscle Strengthening (Resistance Therapy). The ARR should

also provide multiple assessment modes, specifically it should provide objective quantitative information to assess the health of the ankle such as ROM, Joint speed, muscle strength, and muscle proprioception evaluation.

FR5 – Safety & Ergonomics: The ARR should be safe for the patient and therapist to use. The design of the ARR should include multiple, redundant safety measures to prevent any injury and pain to the patient, and also ensure that there are no obstructions to the therapist performing therapy. The control and user interfaces should be intuitive, and easy to use such that the therapist and patient do not have to expend significant physical or cognitive energy in setting up and operating the ARR.

Table 3. ARR Specifications & Target Values

Specifications	Target Value	Notes
ROM in PF/DF [degree]	35/25	Values vary in literature, a representative sample was chosen [1,47]
ROM in INV/EV [degree]	20/15	
Peak Speed [degree per second]	23	This was determined based on motion profile estimation
Peak Resistance Torque of ankle [Nm]	25	Based on passive ankle stiffness model, at max PF position [48]
Position Resolution [degree]	~ 1	5x improvement on Goniometer [9,10,49]
Torque Resolution [Nm]	~ 0.1	Benchmarked to Dynamometer [50]
Speed for Proprioception Testing [degree per second]	~ < 2	Adapted from Threshold to detection of passive motion method – numerical values est. from descriptions of methodology [51]
Misalignment between B-COR and R-COR	< 5 deg < 9 mm	Based on current ARRs misalignment est. [30]

The above list of functional requirements qualitatively captures the problem scope and definition. In addition, Table 3 is a summary of key quantifiable technical specifications for an ideal ARR – this includes ROM and performance targets for the ARR to be able to provide multiple modalities such as continuous passive motion, muscle strengthening, and proprioception evaluation. Target misalignment between the B-COR and R-COR is based on estimates of misalignment of current ARRs. The goal would be to improve on their performance. This specification will be further refined through preliminary human testing where pain and comfort thresholds for misalignment of CORs will be determined. Current literature does not provide clear pain and comfort thresholds for a patient.

4. PROPOSED ARR DESIGN STRATEGY

Based on the above FRs and technical specifications, an ARR design strategy was developed. The optimal ARR is decomposed into individual functional modules or subsystems.

Fig. 4 provides a schematic for the proposed ARR design strategy. Any platform type ARR has a frame module. The frame module is the base or reference ground of the ARR, and consists of elements that will 'ground' the mechanism such that the mechanism will provide DOF to the moving plate with respect to this frame. In addition, the frame will be load bearing, and will bear the weight of the PKM, actuators, sensors, patients' lower limb, etc. This module includes a chair on which the patient can be seated. While platform type ARRs can also be designed for the patients to be seated or lying prone, the former was selected for practical purposes of testing and validating the ARR. The frame would be attached to the lower limb; more specifically to the leg region of the patient. The foot has DOF with respect to the leg region, and if the ARR mechanism shares this ground, its DOFs can be aligned with those of the foot more easily.
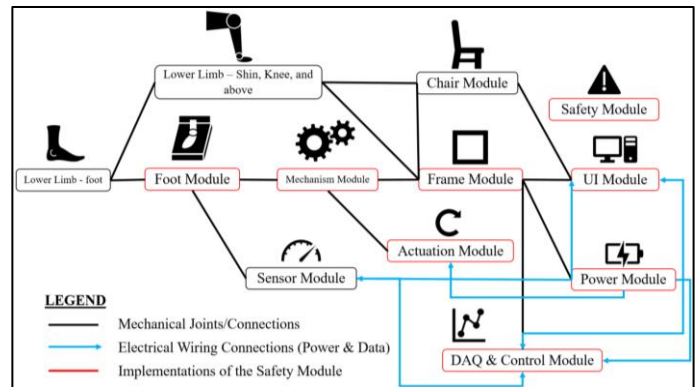

Fig. 4 Schematic of the proposed ARR Design Strategy

As per FR1, the proposed ARR should have at least 2 DOF and as per FR2, it should be able to adapt to individual patient needs. All of the above can be accomplished by the mechanism module. The mechanism should produce a virtual center of rotation that should serve as the R-COR, and leave enough physical space for a patient to insert their foot into the ARR such that their B-COR can be collocated with the R-COR – which meets the FR4. The foot module of the ARR will be the interface of the ARR with the patient's foot. The mechanism of the ARR should impart motion to the foot module, and the foot module would convey that motion to the patient's ankle. This patient's foot will be fully constrained to the foot module, via appropriate straps or other means, to ensure that the torque and rotations transmitted to the foot module by the actuators via the mechanism module are transmitted to the patient's foot as well.

As per FR4, the optimal ARR would require the actuation module to be able to actuate the mechanism to provide therapy, and sensors to provide objective measurements of ankle health parameters such as ROM and muscle strength. The actuation module consists of all actuation elements, including any integrated transmissions (excluding the mechanism module), associated drivers/amplifiers, and feedback sensors necessary for controlled actuation. The sensor module consists of all metrology elements of the system that will provide objective, quantitative information about the position, and speed of the foot with respect to the ankle, and the strength of the muscles that control the motion of the foot. The modules listed above have

coupled relationships based on therapy and assessment mode of the ARR. As per FR5, the proposed ARR would require a user interface for the therapist to control its operation, and an interface for the patient for the purpose of evaluation (especially proprioception evaluation), and for safety (such as a safety stop). This user interface module will have multiple elements that would be placed throughout the system such that they would be easy to reach, and available to the therapist or patient at just the right places (ergonomic considerations).

Lastly, to be able to achieve all of the above requirements, the ARR will be a fully active system, and will require electrical power. In addition, the system will require feedback and control algorithms to control the performance of the ARR in the various therapy and assessment modes, which will be provided by the Data Acquisition & Control Module. A Power Module provides electrical power to the other modules of the system. Based on this proposed design strategy we proceed to further develop a novel ARR, which we call the Flex-ARR with the objective of meeting all the FRs listed in the previous section.

5. CONCEPT GENERATION & PRELIMINARY DESIGN

Based on the functional decomposition provided by the above design strategy, multiple concepts were generated for each module which allowed us to generate specific concepts to meet the FRs defined above. Special emphasis was given to the design of the mechanism module. Concept generation began with the most promising designs from the literature review – modified agile eye and gimbal inspired mechanisms. These designs came closest to meeting all the FRs defined above except FR2 and FR3 where they had their limitations. Any embodiments generated by modifying the above designs in an attempt to satisfy all FRs resulted in increased mechanical complexity. For example, when the agile eye mechanism is modified to meet FR2 and FR3 a change in the geometry or placement of links in the mechanism is required. This resulted in complex motion profiles, reduced ROM, and increased mechanical complexity.

In addition, design modifications did not provide intuitive alignment features for the therapist to use to collocate the B-COR and R-COR. To overcome this challenge it was concluded that if finite compliance is introduced in the constraint directions of the mechanism which can alleviate any conflict between the CORs. That type of mechanism will allow the ARR to self-align the R-COR with the B-COR.

A broader search and survey of mechanisms that provide at least two rotational DOF with a fixed COR, and with features that allow them to meet all defined functional requirements. The broad search led to the compliant PKM used in FlexDex – a minimally invasive surgical tool, see Fig. 5 [18,19]. The mechanism in the FlexDex creates a virtual 2 DOF input joint that is coincident with the surgeon's wrist – allowing the surgeon to control the instrument intuitively, and providing no obstruction to the natural motion of their wrist. The PKM of the FlexDex has DOFs which help accommodate variations in the user's hand sizes which effectively reduces the adjustment features required. It also decouples the rotational DOF which makes it easier to control them [18,19]. This compliant PKM was

modified to meet the requirements of ARRs and developed a mockup of the proposed concept – see Fig. 6 for CAD of the mockup and Fig. 7 (right) for the mockup being used by a person. This mockup focused on the PKM and not the overall ARR system, and was not actuated or equipped with sensors. This mockup was used for user testing and other investigations described in later sections. In Fig. 6, the green axis corresponds to PF/DF motion, the blue axis corresponds to INV/EV motion, and the purple dot represents the R-COR. The frame grounds the PKM and serves as the interface of the patient's leg region to the ARR.
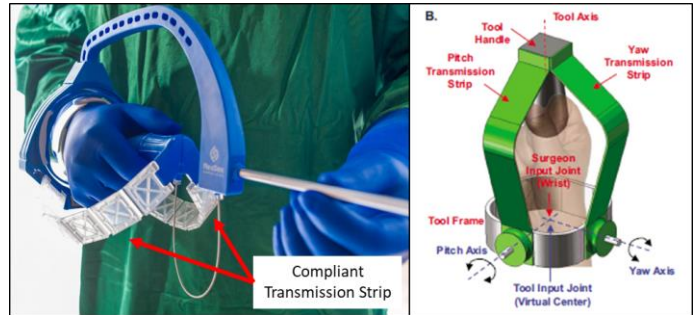

Fig. 5(left) FlexDex device in surgeon's hands with compliant transmission strips, (right) FlexDex Conceptual Design [18,19]

The compliant transmission strips are key to the design and operation of the compliant PKM. They are connected to the frame through a pin joint, and rigidly connected to the foot plate (Fig. 6). The foot plate is the interface between the patient's foot and the mockup – the compliant transmission strips provide the foot plate with 3 DOF with respect to the frame – 2 rotational DOF (INV/EV & PF/DF axis) and 1 translational DOF (along an axis perpendicular to the plane formed by INV/EV and PF/DF axis). A detailed view of a compliant transmission strip is shown in Fig. 7 (left). It consists of multiple parallel living hinges along its length. These living hinges give the transmission strips their rotational DOF about the Z axis, and they were modelled using the existing analytical models of living hinges [52].

The transmission strips are stiff to bending about the X axis and stiff to torsion about the Y axis. Since the transmission strips are typically curved during operation (as shown in Fig. 5 and Fig. 7), the transmission strips undergo bending (about X axis) and torsional (about Y axis) which creates parasitic deformation under loading about the rotational axis of the pin joint (axis along X axis). The compliance of the transmission strips in constraint directions is key to their performance. If they are too compliant the position error in the foot plate due to their parasitic deformation will be large, however if they are too stiff they will not be able to absorb the misalignment of the CORs.

For example, one of the target specification for misalignment of CORs is less than 5 degrees. Hence, for a given stiffness of the transmission strips, if they attempt to deform by 5 degrees to absorb the misalignment, they will apply a reaction torque on the patient's foot. If this reaction torque is too large, the patient will experience pain or discomfort and it will compromise the therapy. This limits how stiff the transmission strips can be. Through experiments the pain thresholds of

patients can be determined. Since this implies that system performance is sensitive to transmission strip stiffness, the transmission strips will be highly modular so that different stiffness can be investigated with human subjects. Multiple factors need to be considered to determine the optimum stiffness of transmission strips.

Based on our analytical and FEA results, the bending stiffness (about X axis) of the transmission strips is far greater than the torsional stiffness (about Y axis). This means that the deformation of the transmission strips will largely be dictated by the torsional stiffness. By tuning the torsional stiffness, we can reduce the position error caused by deformation of compliant parts under loading and yet be compliant enough to absorb misalignment of COR and ensure natural motion of the ankle. The transmission strips designed for the mockup had a bending stiffness of ~ 60 Nm/rad and torsional stiffness of ~ 2 Nm/rad. The analytical and FEA results were confirmed by fabricating the transmission strips and testing their bending and torsional stiffness. The above torsional stiffness is too low for an actuated system, and will require further tuning.

The mockup was evaluated through user testing – the mockup was used by multiple users, and the design team sought feedback on comfort of ankle motion. This testing helped inform design decisions for the detailed design of the Flex-ARR. For example, to meet FR4 the frame of the mockup had alignment features (grooves) that would go around a patient's ankle malleoli and help align the R-COR and B-COR. However, those alignment features did not work with varying user characteristics (gender, physiology, and anthropometry), and since they were a rigid part of the frame, they could not be adjusted. This highlighted the need for a dedicated alignment tool that can adapt to varying users' foot sizes but reliably ensure alignment of R-COR and B-COR.

In addition user testing indicated that the foot plate of the mockup is too heavy, and would require a redesign to reduce the weight for comfort. This user testing informed detailed design decisions.
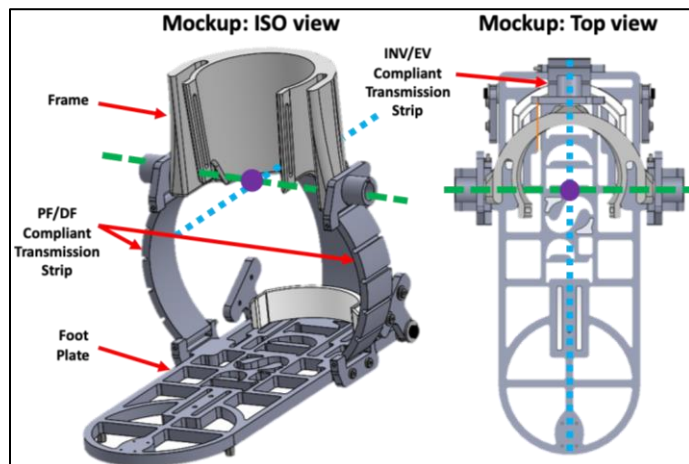

Fig. 6 CAD of novel ARR mockup with compliant transmission strips, frame, and foot plate with R-COR labelled in purple
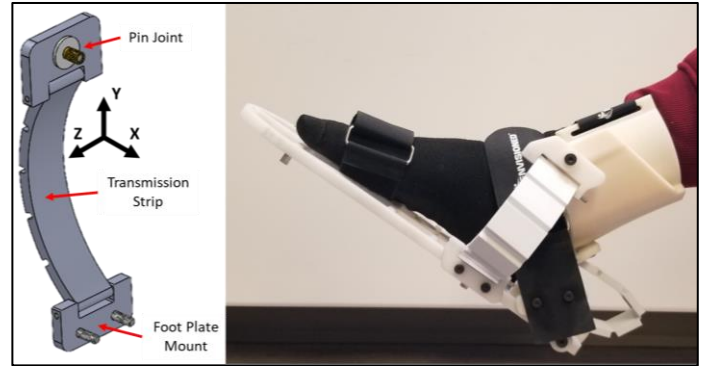

Fig. 7 (left) Detail CAD view of Compliant Transmission Strip, (right) ARR mockup being used in preliminary user testing

6. DETAILED DESIGN OF FLEX-ARR SYSTEM

The detailed design and hardware implementation of the proposed design strategy can be in seen in Fig. 8 (left) which shows the CAD of the proposed Flex-ARR system and a patient's lower limb. The Flex-ARR system consists of multiple modules, which are labelled and color coded in the figure. Flex-ARR consists of the following key components: (1) Ground Frame (dark grey), (2) Chair (dark grey, with light grey plate), (3) Alignment Tool (yellow), (4) Actuator Frame (pink), (5) Motor Housing (orange), and (6) Mechanism & Foot Plate (green and blue). In addition to the above, there is a computer user interface that the therapist uses choose the training mode. The above components correspond to modules presented in the design strategy (Fig. 4). In addition to the above, there is a computer user interface that the therapist uses choose the training mode. In the following subsections, each of the above components and its function is discussed in detail. The Flex-ARR includes multiple adjustments (as shown in Fig. 8); the purpose of all the adjustments is to accommodate variations in patient's lower limb dimensions, and to ensure that the Alignment Tool mates with its corresponding mating feature in the Flex-ARR.

The Flex-ARR system is designed for the following use case. The therapist will first locate the B-COR of the patient using any means at their disposal (e.g. visually or by feeling the malleolus) and mark this location directly on the patient's skin or a sock worn by the patient, while the patient is seated or lying on the examination bed. At this stage, the patient is not strapped to interacting with the Flex-ARR. The Alignment Tool is purposefully designed to ensure collocation of the R-COR with B-COR. As shown in Fig. 8 (right-top), the Alignment Tool is strapped on to the patient's leg region. The therapist can use the locator window adjust the location of the tool, prior to strapping, along the length of the lower limb and adjust the movable indicator fore and aft, after strapping, to ensure that it needle tip of the indicator aligns with the patient's B-COR, when viewed through the locator window. This ensures that the B-COR is at a fixed known location with respect to the alignment tool and its alignment features. By doing so, when the tool's alignment features subsequently mate with the corresponding alignment features on the actuator frame, the B-COR and R-COR will be
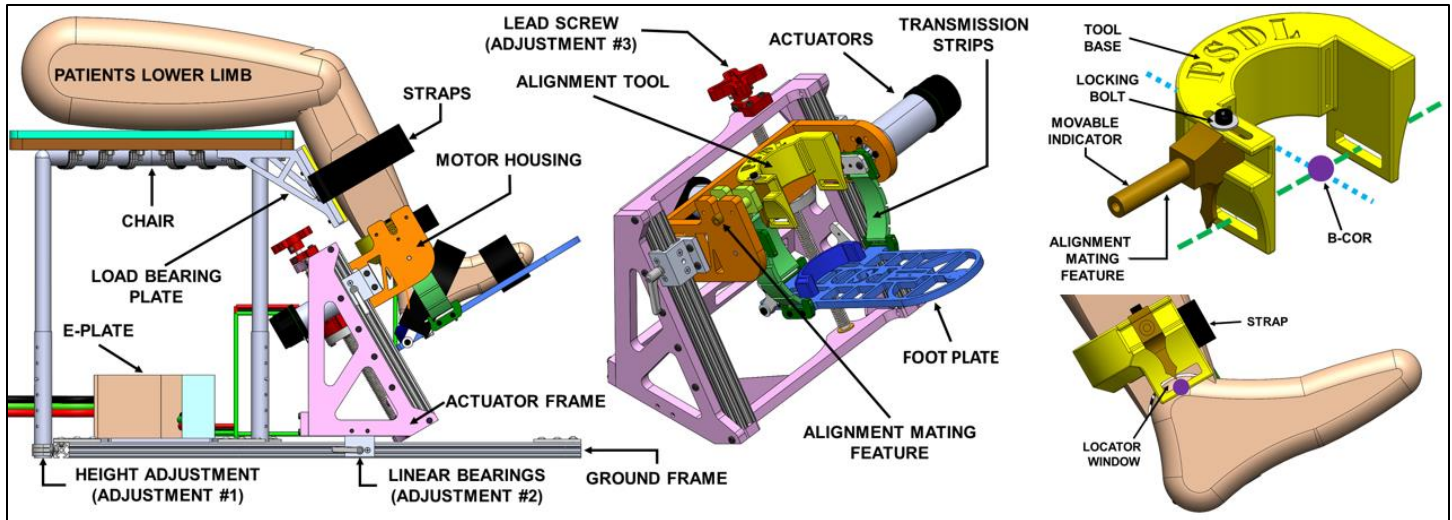
Fig. 8 Flex-ARR Full System CAD (left), Detailed View of the Actuator Frame and associated components (center), Isometric View of the Alignment tool of Flex-ARR (right-top), Alignment tool worn by a patient (right-bottom)

collocated. Once the alignment tool is strapped on the patient's lower limb (Fig.8 lower-bottom), the patient can then interface with the Flex-ARR. The ground frame (Fig. 8 dark grey) is a structural element constructed of 80/20 T-slot aluminum bars. These bars are strong, rigid, and the T-slots allow for easy assembly and integration of other components (e.g. bearings, and fixtures). This constitutes the ground of the Flex-ARR. The Flex-ARR's electronics such as the power supply, microcontroller, and actuator drivers are housed on the E-plate which is part of this frame, and located under the chair. The chair is connected to the ground frame rigidly, and bears the weight of the patient. To accommodate variations in the patient's height or length of lower limb the height of the chair can be adjusted (adjustment #1). Attached to the chair, the load bearing plate (Fig. 8 light grey) is the interface between the patient's leg region and the Flex-ARR. Straps are used to secure the leg such that while the patient is seated on the chair and their leg is strapped, the hip and knee joints are fully constrained.

Once the patient is seated and their leg is strapped, the actuation frame can be adjusted (adjustment #2). The actuator frame is connected to the ground frame through linear bearings (with brakes), and can move towards and away from the chair (adjustment #2). This ensures that for variations in the patient's lower limb (specifically calf dimensions) their lower limb will always approach the actuator frame at a known fixed angle. The motor housing is connected to the actuation frame through linear bearings, and its motion with respect to the actuation frame is controlled through a lead screw (adjustment #3). This adjustment accounts for varying leg region dimensions, as it moves the motor housing towards and away from the patient's foot. The Alignment mating feature (shown in Fig. 8 - right) is part of the motor housing. Using the lead screw, the motor housing is adjusted till the Alignment Tool's alignment mating feature mates with it corresponding feature on the motor housing. This mating ensures that the R-COR is collocated with B-COR. Once these adjustments (#1, #2, and #3) and are done and locked, the

motor housing becomes a rigid extension of the ground frame and is connected to the foot plate via the compliant PKM, which is at the heart of the Flex-ARR.

The PKM is similar to the design used for the mockup, and its compliance will be optimized as discussed earlier to absorb minor misalignment of CORs without causing position error of the foot plate due to deformation under loading. The transmission strips connect to the motor shafts such that actuation torque can be transmitted to the foot plate. The foot plate is connected to the other end of the transmission strips, and serves as the interface between the Flex-ARR and the patient's foot. As mentioned earlier, the transmission strips will be highly modular so that transmission strips of different stiffness can be easily swapped in the Flex-ARR. Once the CORs have been collocated (with the use of the Alignment tool), the foot plate is strapped to the patient's foot. Now the foot plate and patient's foot have no DOF with respect to one another, and any motion transmitted to the foot plate (through the transmission strips) is transmitted to the patient's foot. In this manner, the Flex-ARR is able to isolate control the rotation of the patient's ankle. At this stage, the Flex-ARR becomes ready to begin therapy or assessment, and the Alignment tool, having served its unique purpose, can be removed from the patient's ankle so that it does not interfere with the operation of the ARR.

The Flex-ARR is designed to include position and force sensors which facilitate multiple training modes such as continuous passive motion, muscle strength, and assessment such as proprioception evaluation. The control scheme and user interface will allow the therapist to set ROM targets for the patient, and customize the Flex-ARR performance to meet the individual needs of the patient. Lastly, various safety considerations such as safety stop switches, current and power limiters protect both the patient and the Flex-ARR from damage. The Flex-ARR detailed design is complete, and its fabrication, development of control scheme, and associated experiments are discussed in the next section.

7. FUTURE WORK

Future work includes Flex-ARR system fabrication and testing. Once fabricated, the system testing will involve verification of system performance, and proper functioning of all safety features to ensure that testing with humans can be performed with no risk. As mentioned before, to determine pain thresholds of patients, human subject testing will help refine the stiffness of compliant transmission strips. The highly modular transmission strips will allow the investigation of multiple stiffness using the same Flex-ARR system. In addition to the verification testing, the Flex-ARR performance will be validated with human subject testing to ensure its safety and performance benefits. Human subject testing will include evaluating the performance of the Flex-ARR in its various operation modes such as continuous passive motion, resistance training, and assessment modes as such proprioception evaluation. In addition to sensor based data, subjective human experience will be captured through survey and interviews of human subjects before, during, and after using the Flex-ARR.

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