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Rehabilitation Process and Outcome

An Assistance-as-Needed Control Paradigm for Robot-Assisted Ankle Rehabilitation

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ABSTRACT: Robots have been developed for treatment and rehabilitation of ankle injuries. Two reviews have been conducted involving the effectiveness of robot-assisted ankle rehabilitation and ankle assessment techniques respectively to investigate what the optimal therapy is. This study proposes an assistance-as-needed (AAN) control paradigm for potential use in robot-assisted ankle rehabilitation based on the review results. This AAN control strategy will consider real-time ankle assessment and make rehabilitation more effective.

KEYWORDS: ankle rehabilitation, robot-assisted, assistance-as-needed

CITATION: Zhang et al. An Assistance-as-Needed Control Paradigm for Robot-Assisted Ankle Rehabilitation. *Rehabilitation Process and Outcome* 2014:3 15–17 doi:10.4137/RPO.S12340.

RECEIVED: January 25, 2014. **RESUBMITTED:** February 25, 2014. **ACCEPTED FOR PUBLICATION:** February 26, 2014.

ACADEMIC EDITOR: Thilo Kroll, Editor in Chief

TYPE: Short Commentary

FUNDING: Authors disclose no funding sources.

COMPETING INTERESTS: Authors disclose no potential conflicts of interest.

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Robots have been developed for treatment and rehabilitation of ankle injuries. Wearable robots are aimed at improving ankle performance during gait, whereas platform-based robots focus on improvement of ankle performance.[1–6] A recent systematic review conducted by Zhang et al[7] summarized various robot-assisted ankle rehabilitation techniques. The review concluded that the majority of them were beneficial for ankle recovery, but the effectiveness of robot treatment was not clear because of a lack of universal evaluation criteria. It also revealed that few took real-time ankle kinematics and kinetics into consideration when programming robotic control strategies, and AAN control strategy was proposed for optimal ankle therapy.

The optimal therapy should be tailored to the condition of each patient through a performance-based control algorithm. Hogan et al[10] suggested that the form of therapy might be more important than its intensity: muscle strengthening offers no advantage over movement training. Experienced rehabilitation therapists advocated AAN control strategy, which refers to the principle of helping patients perform a movement with minimal amount of external assistance possible.[11] In AAN training strategies, robotic devices only supply as much effort as patients need to accomplish training tasks, so voluntary participation is encouraged; whereas, in conventional robotic trajectory tracking training system, patients' active participation is not a concern. Studies[12–14] were conducted on both animals and humans to compare active with passive training regimes. The results indicated that subjects' voluntary participation led to more effective training. In terms of implementation, however, the concept of AAN is still vague, because different levels of assistance could be applied according to specific applications. Typical AAN schemes determine the amount of assistance based on task accuracy in virtual reality, and it is a multi-criteria optimization problem.[2,3,15,16] While these studies demonstrated that training regimes with different AAN paradigms reduced ankle motor impairment as assessed with various outcome measures, these methods used are not optimal nor very safe because they ignored actual

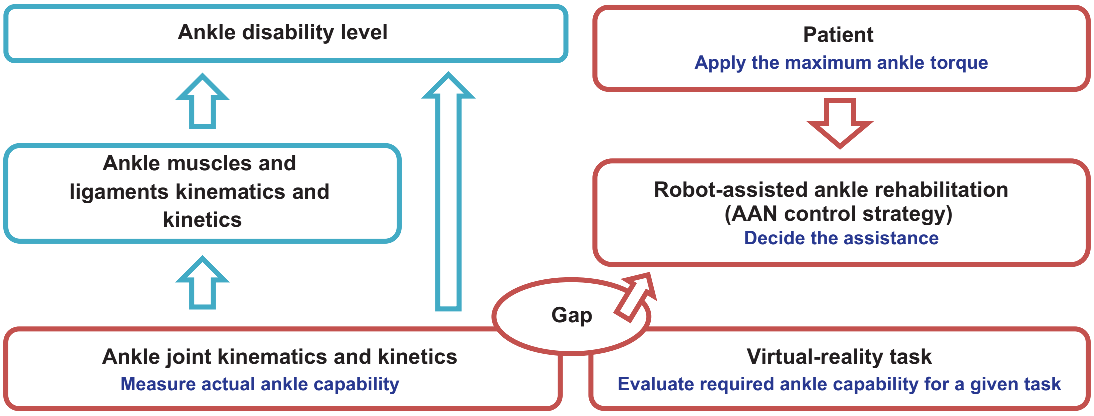

Figure 1. The block diagram of the proposed AAN robot-assisted ankle rehabilitation strategy.

ankle disability level. Thus, an AAN control paradigm of robot-assisted ankle rehabilitation was proposed in this study with consideration of actual ankle capacity.

Another review[17] conducted by our group discussed various ankle measurement and assessment techniques as well as their potentials when combined with robot-assisted ankle therapy. It included 16 qualitative and 60 quantitative studies, and concluded that these qualitative methods were not suitable for real-time monitoring in robot-assisted therapy though they were usually reliable for certain patients, while quantitative techniques showed great potentials. Further, the majority of quantitative techniques were reliable in measuring ankle kinematics and kinetics, but were usually only available for use in sagittal plane. Limited studies determined ankle kinematics and kinetics in all three planes (sagittal plane, transverse plane, and frontal plane) where motions of ankle joint and subtalar joint actually occur.[18]

In this article, we would recommend to combine AAN robot-assisted ankle rehabilitation technique and real-time ankle assessment. Figure 1 shows the flow diagram of a novel AAN control strategy for potential use in robot-assisted ankle rehabilitation. The red part of this block diagram is the key to the realization of the proposed AAN control strategy in robot-assisted ankle rehabilitation. The blue part provides further information involving ankle muscles and ligaments that may be required for more accurate ankle disability assessment. The patient is encouraged to achieve the best performance in virtual-reality task and apply the maximum ankle capability when real-time ankle assessment including kinematics and kinetics is conducted. The actual ankle capacity (it can be assumed to be ankle torque in this paradigm) is compared with the required ankle capability for a given task, which determines the gap that is the basis of the proposed AAN robot-assisted ankle rehabilitation. Based on measured ankle joint kinematics and kinetics, the corresponding kinematics and kinetics of ankle muscles and ligaments can be obtained by inverse dynamics based on a biomechanical ankle model. Further, ankle disability level could be quantified according to the kinematics and kinetics of ankle joint, muscles, and ligaments based on a predefined criterion.

Siegler et al[19] showed neither ankle joint nor subtalar joint was acting as an ideal hinge joint, and motion of ankle–foot complex is the result of rotations at both the ankle and subtalar joints. To be specific, the contribution of ankle joint to dorsiflexion/plantarflexion of ankle–foot complex is larger than that of subtalar joint, the contribution of subtalar joint to inversion/eversion is larger than that of ankle joint, and ankle and subtalar joints have an approximately equal contribution to internal/external rotation movements. Therefore, the assessment of actual ankle capacity as well as the required value for a given task should be movement specific, which will further improve the effects of AAN robot-assisted ankle rehabilitation.

Author Contributions

Conceived and designed the experiments: MZ, TCD, AN and SX. Analyzed the data: MZ. Wrote the first draft of the manuscript: MZ. Contributed to the writing of the manuscript: MZ, TCD, AN and SX. Agree with manuscript results and conclusions: MZ, TCD, AN and SX. Jointly developed the structure and arguments for the paper: MZ, TCD, AN and SX. Made critical revisions and approved final version: MZ, TCD, AN and SX. All authors reviewed and approved of the final manuscript.

DISCLOSURES AND ETHICS

As a requirement of publication the authors have provided signed confirmation of their compliance with ethical and legal obligations including but not limited to compliance with ICMJE authorship and competing interests guidelines, that the article is neither under consideration for publication nor published elsewhere, of their compliance with legal and ethical guidelines concerning human and animal research participants (if applicable), and that permission has been obtained for reproduction of any copyrighted material. This article was subject to blind, independent, expert peer review. The reviewers reported no competing interests. Provenance: the authors were invited to submit this paper.

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