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A robot-based hybrid lower limb system for Assist-As-Needed rehabilitation of stroke patients: Technical evaluation and clinical feasibility

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ABSTRACT

Background: Although early rehabilitation is important following a stroke, severely affected patients have limited options for intensive rehabilitation as they are often bedridden. To create a system for early rehabilitation of lower extremities in these patients, we combined the robotic manipulator ROBERT® with electromyography (EMG)-triggered functional electrical stimulation (FES) and developed a novel user-driven Assist-As-Needed (AAN) control. The method is based on a state machine able to detect user movement capability, assessed by the presence of an EMG-trigger and the movement velocity, and provide different levels of assistance as required by the patient (no support, FES only, and simultaneous FES and mechanical assistance).

Methods: To technically validate the system, we tested 10 able-bodied participants who were instructed to perform specific behaviors to test the system states while conducting knee extension and ankle dorsal flexion exercises. The system was also tested on two stroke patients to establish its clinical feasibility.

Results: The technical validation showed that the state machine correctly detected the participants' behavior and activated the target AAN state in more than 96% of the exercise repetitions. The clinical feasibility test showed that the system successfully recognized the patients' movement capacity and activated assistive states according to their needs providing the minimal level of support required to exercise successfully.

Conclusions: The system was technically validated and preliminarily proved clinically feasible. The present study shows that the novel system can be used to deliver exercises with a high number of repetitions while engaging the participants' residual capabilities through the AAN strategy.

1. Introduction

Rehabilitation is important to improve the motor function in stroke survivors [1–3]. Despite rehabilitation, approximately 35% of stroke survivors with a degree of leg paresis show no motor recovery [4]. For individuals who are severely affected by a stroke and confined to a bed or wheelchair in the early phase the treatment options for intensive rehabilitation are limited [1]. During this period [5], the neural system is specially primed for recovery through neuroplastic mechanisms [5,6]. Therefore, enabling these patients to exercise despite the severe limitations could strongly facilitate the outcome of the rehabilitation [6–10].

Conventional therapy during which repeated movements of a patient's leg(s) are performed by a therapist may be offered to the patient while being bedridden. However, this type of exercise is very strenuous for therapists, who report some of the highest rates of work-related injuries [11]. Hence, there is a need for rehabilitation systems that may relieve therapists physically to avoid injuries while simultaneously releasing their time for other important tasks such as communicating with the patients or assessing their progress [12] while avoiding injury.

Maier et al. 2019 [13] have identified 15 principles of exercise that are important for optimizing the rehabilitation outcome including massed practice, optimal dosage, progressive increase in difficulty, provision of multisensory stimulation, and explicit and implicit feedback [13]. Based on the work by Maier et al. 2019, an ideal exercise program should incorporate frequent and intensive sessions with time

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to rest between the sessions [13]. Furthermore, the exercise difficulty should be tailored to the patient's capabilities and the exercise should integrate multisensory stimulation as this appears to facilitate/modulate sensorimotor recovery [13]. Finally, the exercise should incorporate feedback to the patients both regarding their performance (e.g., accuracy in hitting a target) and how to improve in the next trials (e.g., "lift your foot higher") [13].

Robotic interventions may provide a suitable exercise paradigm for patients in the early stages of the rehabilitation encompassing the aforementioned principles for effective exercising [13]. Additionally, robot-based therapy will limit the difference in therapy caused by the variance in the skills of the physiotherapists ensuring a uniform rehabilitation for all patients [9]. A common approach to delivering robotic training is to repeatedly move the limbs of the patients. This allows performing many repetitions even for individuals with severe disabilities. However, in some cases, the patients do not actively participate in the exercise, which can significantly limit the effectiveness of the rehabilitation [14,15]. Even when the patients participate actively during robotic training, they may still exert less effort than during conventional therapy reducing the effectiveness of the exercise; a behavior commonly called "slacking" [15].

Functional electrical stimulation (FES) is another well-established approach for the rehabilitation of patients with severe mobility impairments [16–18]. FES relies on the delivery of electrical pulses to activate motor nerves. This allows patients to generate forceful muscle contractions even if they have little to no voluntary muscle control. However, FES is associated with early onset of fatigue [16,19] and poor control of force [20], thus limiting the quality and amount of exercise delivered to the patient. Additionally, while actively stimulating neuromuscular tissue, FES does not necessarily involve active movement initiation by the patient. However, this is one of the key principles promoting the improvement of motor function after stroke [21–23]. To enable this, the triggering of FES could be based on the voluntary effort of the patient, which can be implemented by monitoring and detecting muscle activation.

By combining FES and robotics, the drawbacks that characterize these technologies when applied individually can be mitigated. For instance, FES can be used to counteract the patients' passivity during robotic exercising as it ensures muscle activation. Likewise, a robot can provide precise force control and delay the onset of muscle fatigue [24,25]. Additionally, both passivity and early fatigue can be reduced further by implementing the so-called assist-as-needed (AAN) paradigm. In this approach, the intervention automatically adapts to the patient's capabilities, supports them only to the necessary degree, and allows them to perform the movements by themselves or activate their muscles as much as they can [23,26]. Additionally, utilizing the AAN strategy is further suggested to improve motor learning and rehabilitative outcomes [22,23,27,28]. AAN can be provided using different strategies, e.g., by adjusting the amount of support to complete the exercise [28–30] or by providing corrective forces only when the patients' movements deviate significantly from the reference trajectory (a so-called virtual tunnel) [27,30,31]. As shown in the present study, an additional advantage of a hybrid system combining FES and robotics is that AAN can also be implemented by changing the support modality, e.g., using either robot, FES, or both methods simultaneously to assist.

Previous exercise systems for bedridden patients with severe limitations in their lower extremities include a resistive exercise device using a flywheel [32], a robot providing cyclic movements comparable to natural gait (NEUROBike) [33], a passive ankle mobilizer (Toe-Up!) [1], a robotic tilt-table with leg plates for passive stepping combined with electrical stimulation (ERIGO) [34,35], portable suspended footplates for active exercise (LEX) [36], and combined electrical stimulation and in-bed cycling [37]. Of these systems, the flyweel [32], NEUROBike [33], Toe-Up! [1], and LEX [36] are not hybrid, and thus do not benefit from combining robotics and FES. Further, neither of these systems actively and continuously consider the patients' current capabilities as they do not incorporate AAN, and do not modulate the assistance provided to the patient. Instead, the patient is passive while the system generates movements mechanically [1,33], or by delivering FES with fixed parameters [34,35,37]. In some cases, the patient is expected to be active but receives no support [32,36].

This study aims to present the technical validation and demonstrate the feasibility of a rehabilitation system providing lower limb movement assistance to severely affected stroke patients while utilizing the patients' own volition and effort to promote recovery. The system implements a novel AAN approach that combines mechanical assistance and FES, and is designed to support the patient in generating leg movements while being bedridden or lying on an examination bench. The system is built on the robotic manipulator ROBERT® (Life Science Robotics ApS), as it has a uniquely flexible approach to bedridden rehabilitation and is greatly primed for an AAN control paradigm, as it is easy to de-/activate active support of selective exercises. In addition, this work builds on a previous study by Petersen et al. 2020, in which the robotic manipulator ROBERT® (Life Science Robotics ApS) was combined with EMG triggered FES to provide hybrid support for neurorehabilitation [38]. The system developed in [38] applied FES upon detecting EMG in the monitored muscles and, hence, did not consider the participants' capability of performing the exercise voluntarily (without assistance). This potentially limited their active participation in the exercise, which is essential for rapid neuromuscular recovery [22,23,39]. The role of ROBERT® in [38] was to provide resistance to the exercise and guide the movement pattern. In the present work, the system developed in [38] was extended by implementing a novel AAN strategy with three distinct levels of support: No support, FES, or FES combined with mechanical assistance. The implemented AAN method monitored the effort of the participants to provide an appropriate level of support, namely, the level of assistance that is just enough for the participant to perform the exercise. This should ensure that they remain engaged to the maximum of their abilities, which is suggested to lead to increased rehabilitative outcome [23,27,28,39]. Additionally, this can extend the duration and scope of the training. The novel system was developed as a hybrid solution to limit the slacking effect of pure robotic interventions, ensure active and voluntary involvement of the patients and their muscles in the exercise, delay the onset of fatigue, and apply mechanical and/or electrical assistance according to the patients' capability. Here we describe the overall system, present its technical validation in able-bodied participants, and preliminarily assess its clinical feasibility by testing the system on two stroke patients.

2. Methods

The system developed in the present study was designed to deliver only the level of assistance needed to complete the exercise. This was achieved by assessing the patients' own effort at each repetition of the exercise to determine which assistance level to provide. The assistance levels were implemented by activating and/or combining the available support modalities, namely, no support (patients' volitional effort), FES delivery, mechanical assistance, or both (as described in the Section AAN state machine). Finally, the system was designed to provide exercises of varying difficulty and to help the patients adhere to a specific movement trajectory to promote motor learning [13].

2.1. System components

The developed system was composed of:

- The rehabilitation robot ROBERT®.
- An FES system with disposable electrodes (Durastick Premium, CefarCompex).
    - Technical validation: NoxiSTIM, JNI Biomedical, Denmark.
    - Clinical feasibility: RehaStim, Hasomed, Germany.

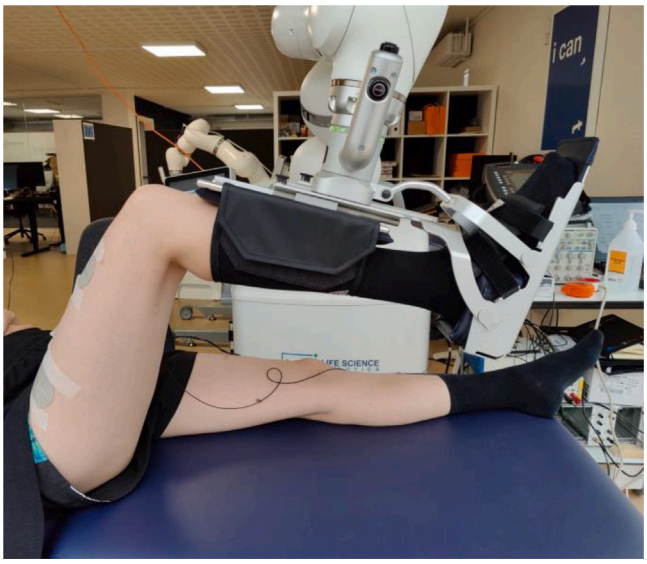

Fig. 1. ROBERT® is a seven-degree-of-freedom robotic manipulator that can move the lower limb of a patient in a lying position. The participant's leg was attached to the end effector of ROBERT® through a foot brace.

- An EMG amplifier with Ambu® Neuroline 720 electrodes.
    - Technical validation: Custom-made EMG amplifier, Aalborg University, Denmark.
    - Clinical feasibility: RehaIngest, Hasomed, Germany.
- A PC running the control state machine and communicating with ROBERT®, the EMG amplifier, and the FES device.

Note: In the clinical feasibility test, the stimulator and EMG recorder differed from the ones used in the technical validation. However, the system setup, calibration, and functioning were identical during both assessments. During the technical validation, the system was a prototype, whereas the system used in the clinical feasibility test was a matured version of the system.

ROBERT® is a seven-degree-of-freedom robotic manipulator employing impedance control that can move the lower limbs of a patient in a lying position [38,40,41] (see Fig. 1). In the present work, the robot produced a resistive force opposing the movement of the participant to impose an active and engaging resistive exercise, while compensating for the pull of gravity on the participant's leg by providing vertical assistive force. In addition, the robot enforced a virtual tunnel, which prevented excessive radial deviation from the defined trajectory, by applying a corrective force proportional to that deviation. Furthermore, the system provided two auditory cues to the participants; one denoting when the robot had returned their leg to the starting position of the exercise and they could begin a new exercise repetition, and a second when the end of the movement trajectory was reached, and they could allow the robot to guide their leg back. In the novel system, the robot was also programmed to provide mechanical assistance to produce the movement when needed as explained later. Finally, the system recorded the position of the end effector at a sampling frequency of 50 Hz to estimate the velocity of the movement.

The electrical stimulation frequency and pulse duration were fixed at 30 Hz and 300 μs [16], respectively, while the pulse amplitude was adjusted individually for each muscle and participant as described in the Section System calibration.

The recorded EMG was used to detect the participants' voluntary effort (intention to move) and was implemented as a "trigger" in the AAN state machine. The EMG was recorded in a differential configuration at 1000 Hz and digitally filtered using a 4th order Butterworth bandpass filter (f_L: 20 Hz, f_H: 40 Hz) and a 2nd order Butterworth notch filter (f_L: 48 Hz, f_H: 52 Hz).

ROBERT®, the EMG, and FES systems were controlled by a state machine described in the Section AAN state machine and implemented on a host PC. During the technical validation, the PC was connected to ROBERT® through a LAN connection, and to the FES system and the EMG amplifier through a data acquisition and signal generation device (National Instruments USB-6212). In the clinical feasibility tests, the PC was connected to the EMG amplifier and the FES system directly through a USB connection.

It should be noted that the control scheme implemented in the present study does not relate to the ROBERT® platform itself. In the development of novel rehabilitation systems, the low-level control of the system is often required to be designed and studied, such as in [42,43]. However, the present study developed a novel system on the existing ROBERT® platform, and thus, the control scheme studied concerns only the high-level control of the synergy between ROBERT®, the EMG detection system and the FES delivery system.

The system setup required attaching the participant's foot to the end effector of ROBERT® through a foot brace, mounting two stimulation electrodes and three EMG recording electrodes, and connecting the electrodes to the stimulator and the EMG amplifier, respectively. See an overview of the system in Fig. 2.

For safety the ROBERT® had a built-in "safe mode", which activated upon detecting high torques in the robotic joints, indicating patients performing unintended movements or resisting the movement performed by the robot (during mechanical assistance). Upon activating, "safe mode" would lock the robot in its path and support the patient's leg until the experimenter could manually move the robot to a safe position for the patient's leg. This feature was designed to prevent harmful situations, such as during spastic events. Additionally, the system was equipped with emergency stops for the robotic device and the FES delivery system.

2.2. System calibration

The system required several calibration steps. Firstly, the exercise to be administered had to be defined by manually guiding the end effector of ROBERT® through the desired trajectory, while the lower leg of the participant was attached to the robot's end effector through the custom brace. A team of physiotherapists and doctors determined that knee extension (KE) and ankle dorsal flexion (ADF) were the two most relevant exercises to focus on during the first tests of the system due to their relevance to standing and walking abilities.

Secondly, the resistance of ROBERT® and the amplitude of the FES were calibrated according to the procedure defined in Leerskov et al. 2022 [40]. In brief, the resistance of ROBERT® was set to a level that was sufficient to compensate for the gravity, i.e., to avoid the participants' legs falling downwards during the KE exercise. Then, the amplitude of the FES was set high enough to allow completing the exercise trajectory at this resistance level. If the participant could not tolerate this stimulation amplitude due to discomfort, the resistance of ROBERT® was lowered and the stimulation intensity recalibrated.

Finally, a threshold for the EMG trigger was determined. The threshold methods developed for the system referred to as 'SDx2' and 'SDx3', were tested in stroke patients and presented previously by Rikhof et al. 2022 [41]. In summary, the thresholds were calculated based on three seconds of resting EMG recorded while the participants relaxed their legs supported by the robot in the starting position of the exercise to be performed. The thresholds were then set to the mean of the three seconds of resting EMG plus two (SDx2) or three (SDx3) times the standard deviation of the resting EMG [41]. In the present work, the SDx3 was used by able-bodied participants during the technical validation while SDx2 was used by stroke patients during the clinical feasibility test. The calculation of the EMG trigger threshold was switched from the SDx3 to the SDx2 method in the clinical

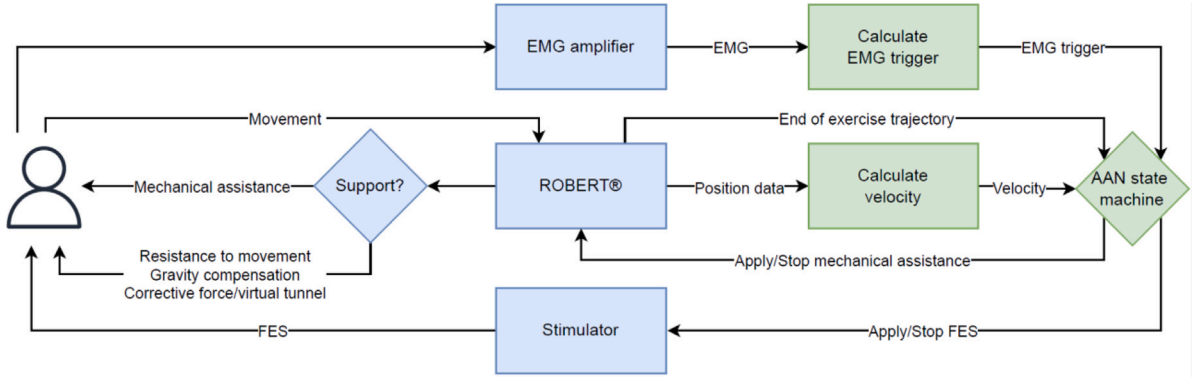

Fig. 2. An overview of the system developed in the present study. Blue elements are the system components, whereas green color indicates processing and control implemented on the PC. Participants were connected to the robot via a custom foot brace attached to ROBERT®. The electrodes were placed on the limb and connected to the EMG amplifier and the stimulator as shown in Fig. 4. The host PC detected EMG triggers and computed the velocity of the movement (see Section System calibration). EMG triggers, the movement velocity, and the indication about reaching or not the end of the exercise trajectory were transmitted to the AAN-state machine, which determined the appropriate level of support (see Section AAN state machine and Fig. 3 for the logic behind state transitions). The support comprised no support, FES, or FES plus mechanical assistance. Upon reaching the end of the exercise trajectory, the support was terminated, and the leg of the participant was brought back to the initial position (start of the exercise). The required level of support was determined on a repetition-by-repetition basis. When ROBERT® did not provide mechanical assistance, it instead generated resistance to the movement performed by the participant, gravity compensation, and corrective forces for the participant to adhere to the predefined trajectory formed as a virtual tunnel. The host PC kept track of the exercise repetitions and terminated the session when the specified number of exercise repetitions was reached.

feasibility test, partly due to the results of the technical validation and partly due to the results obtained by Rikhof et al. 2022 [41]. The EMG trigger thresholds introduced here differ from those used by Petersen et al. 2020 [38]. Petersen et al. 2020 reported that 20.5% and 15.5% of their EMG triggers for KE and ADF, respectively, were premature and produced by noise [38]. We expected that this new EMG trigger threshold calculation method would resolve this issue.

During system operation, an EMG trigger was generated if the mean of the rectified EMG in two out of three consecutive 50-ms windows was above the adopted threshold and indicated the participants' intention to move. Additionally, the movement velocity was estimated by differentiating the position of the end effector recorded by ROBERT® and then smoothing the obtained signal using a 10-sample moving average filter as in Leerskov et al. 2022 [40].

Following the calibration of the system there was no reassessment nor online readjustment of the EMG-trigger threshold and FES amplitude, except, in the clinical feasibility test it was possible to adjust the EMG-trigger threshold online. It was assumed that the participants EMG activity and their responses to FES would remain constant for the duration of the experiment.

2.3. AAN state machine

The level of support provided to the user was determined by an AAN state machine (Fig. 3) and assessed during each repetition of the exercise as explained in the following.

If the participants were able to complete the exercise repetitions voluntarily, they were not assisted (AAN state: *Vol*) in order to maximize the use of their own resources. If a participant was not able to complete an exercise repetition, FES was administered (AAN state: *FES Trig* or *FES Auto*) to produce the required force to complete the repetition. The *FES Trig* state was activated when the participant was able to initiate a movement but was unable to complete it, while the *FES Auto* state was activated when the participant was too weak to even initiate a movement. Hence, the output of *FES Trig* and *FES Auto* states were the same (FES), but the transitions to the respective states were different. The states were implemented separately as they represented different functional levels of the patient, i.e., whether they were able to initiate movement on their own or not, which is valuable information in a rehabilitation setting. FES was chosen as the first level of assistance because it engages actively the participant's own muscles while also producing substantial afferent input, both directly by stimulating the sensory fibers and indirectly through the induced movements. If FES alone was insufficient to complete the exercise repetition, determined by the movement velocity resulting from the applied FES, *FES Trig* or *FES Auto* would progress to the AAN state *FES & Mech*, and the robot would additionally provide mechanical assistance as the second level of support. The mechanical assistance was provided by disabling the resistance of ROBERT® opposing the movement and then activating the position controller that moved the participants' limb towards the end of the desired trajectory. Using these three levels of progressive assistance from no support to FES only and combined FES and mechanical assistance (implemented collectively in four states), the participants were guaranteed to accomplish the exercise while being encouraged to use as much remaining capacity as possible to initiate and/or perform the movement actively. When the participants' legs reached the end of the exercise trajectory, the assistance was deactivated, and the robot moved the leg to the starting point of the trajectory. A new repetition was then administered unless the preset number of repetitions had been reached (end of exercise).

To determine the level of assistance required by the participant, the state machine monitored the EMG trigger and the velocity of the end effector (see Section System calibration), the wait time (time without an EMG trigger), and whether the end of the exercise trajectory had been reached. The EMG indicated if the participant actively contributed to the exercise or at least attempted to move, and the movement velocity was used to determine if the participant could move the leg along the trajectory at a given assistance level. The wait time had a limit of 10 s. If this threshold was reached the system concluded that the current exercise repetition was unlikely to be completed by the participant voluntarily, and would therefore administer FES (*FES Auto*). The detection of the end of the trajectory was used by the system to deactivate all assistance and to restart an exercise repetition unless the predefined number of exercise repetitions had been reached, at which point the exercise was stopped. During the technical validation, a successful movement was defined as the ability to maintain an average velocity equal to or higher than 20 mm/s. In the clinical feasibility test, the minimum velocity was lowered to 5 mm/s and 1 mm/s for KE and ADF, respectively, to reflect the reduced motor capabilities of the patients. Additionally, the wait time was lowered to 5 s. This adjustment was made as an initial test on stroke patients revealed that the velocity thresholds were unnecessarily high, and the *FES Auto* state wait time was assessed as being inappropriately long for clinical application in pilot experiments. Hereafter, these values will be referred to as the velocity thresholds.

Vol was the default state for each new exercise repetition, and it was active as long as the participant could perform the exercises voluntarily

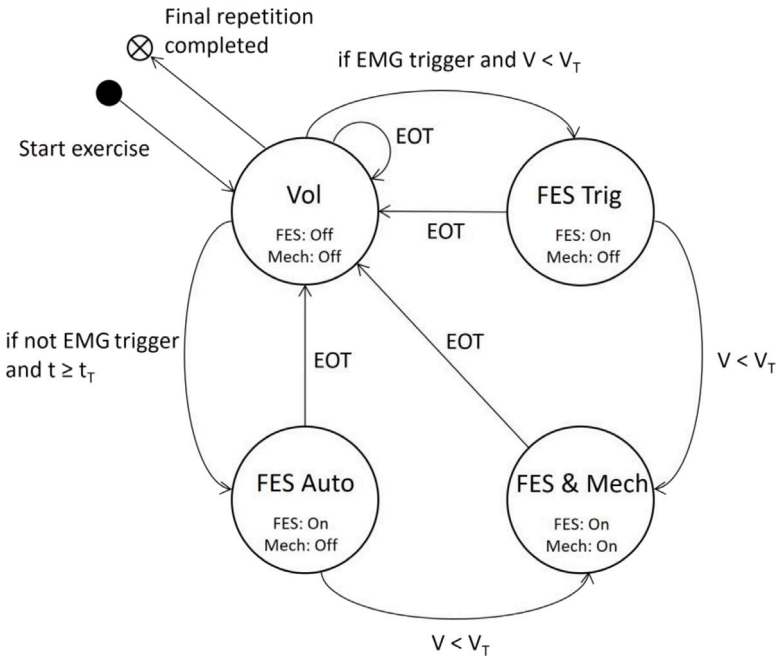

Fig. 3. The state machine for the control of the assist-as-needed (AAN) training protocol implemented in the system. The circles indicate the four different states and the arrows are the transitions between them. The small filled circle indicates the start condition, and the small empty circle with a cross indicates the end condition. The inputs monitored by the state machine for the *Vol* state, were the EMG trigger detection, the velocity of the end effector, the wait time (time without an EMG trigger), and the indication of whether the end of the exercise trajectory had been reached. The inputs for the *FES Trig* and *FES Auto* states were the end effector velocity and the indication about the end of the exercise trajectory. The state *FES & Mech*, once triggered, would always result in a completed exercise repetition, and therefore the input to this state was only the indication that the end of the exercise trajectory had been reached. When the repetition finished, FES was turned off, and the robot moved the leg to the starting position unless the exercise was ended (the last repetition had been completed). *Vol*: Voluntary, *FES Trig*: EMG triggered FES, *FES Auto*: Auto-triggered FES, and *FES & Mech*: FES + Mechanical assistance. EOT: End of trajectory; V: Velocity; V_T: Velocity threshold; t: Wait time; t_T: Time limit.

with their own effort. In this state, the system monitored both the EMG trigger and the movement velocity. If the average movement velocity of the participant decreased below the velocity threshold consistently during a 2-s interval, this was considered as an indication that the participant could not move using their own effort. If this coincided with the detection of an EMG trigger, the state machine progressed to the *FES Trig* state and FES was administered.

If the participant could not generate an EMG trigger within a 10-s interval (5-s interval in the clinical feasibility test) while in the *Vol* state, this was interpreted as a sign of excessive weakness or fatigue, and the state machine transitioned to the *FES Auto* state and applied FES.

If the average movement velocity was consistently below the velocity threshold for more than 2 s while FES was being administered (*FES Auto* or *FES Trig* states active, see Fig. 3), the state machine transitioned into *FES & Mech* state and the robot provided mechanical assistance in addition to FES.

In the following *FES Trig*, *FES Auto*, and *FES & Mech* is referred to as *Trig*, *Auto*, and *Mech*, for simplicity.

2.4. Experimental procedure

Two experiments were conducted, namely, a technical validation conducted on able-bodied participants at Life Science Robotics ApS, Aalborg, Denmark, and a preliminary clinical feasibility test conducted on two stroke patients at Roessingh Research and Development, Enschede, the Netherlands. Both experiments were conducted according to the Helsinki Declaration and the experiments were approved by the local ethical committees as explained in the following.

2.4.1. Participants

Ten able-bodied volunteers were recruited to participate in the technical validation (five males, mean age: 28.3 ± 5.5 years). The inclusion criteria were no known neurological or muscular diseases.

Table 1
Overview of patient characteristics. LE: Lower Extremity.

	Time since stroke (days)	Fugl-Meyer assessment LE score	Motricity index LE
Patient 1	29	3	0
Patient 2	39	16	39

Volunteers were excluded if they (1) were pregnant, (2) had implanted devices, e.g., a pacemaker, (3) lacked the ability to cooperate, or (4) were diagnosed with cognitive deficits. The study was approved by The North Denmark Region Committee on Health Research Ethics (N-20210015) and all participants signed informed consent forms before inclusion.

Data from two patients (two males, mean age: 47.5 ± 2.1 years) related to AAN state progression and fatigue scores were taken from a comprehensive clinical feasibility study with additional participants (to be reported separately) to assess the initial feasibility of the AAN approach in stroke patients. The patients' characteristics and their performance during the clinical feasibility test are shown in Table 1. Stroke patients were recruited if they (1) had a (sub)acute stroke and (2) hemiparetic lower extremity. Stroke patients were excluded from the clinical feasibility study if they (1) had premorbid disability of the lower extremity, (2) skin lesions at the hemiparetic leg, (3) a pacemaker, (4) contraindications for mobilization, (5) severe cognitive impairments, or (6) were pregnant. The clinical study was approved by the METC East-Netherlands (NL76919.091.21) and the patients signed informed consent forms before inclusion.

2.4.2. Participant preparation

The participants were lying on a medical bed and their lower leg was attached to the end effector of ROBERT® through a foot brace (see Fig. 1). In able-bodied participants, the right leg was attached to

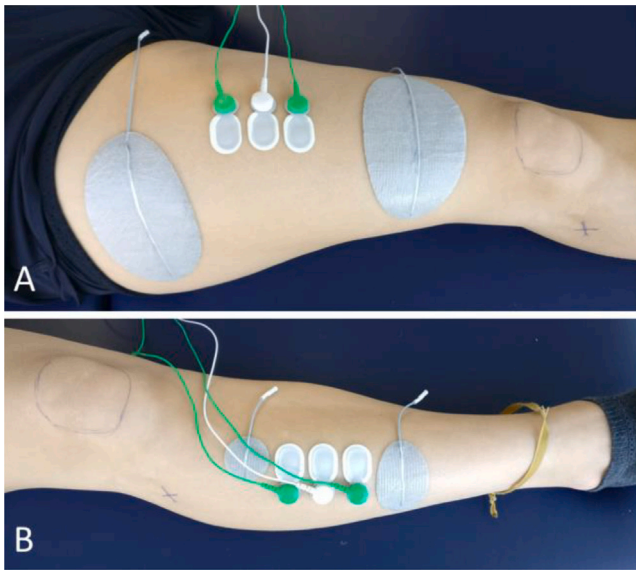

Fig. 4. An overview of the two electrode configurations used for KE and ADF, respectively. A: For KE, the electrodes were placed medio-laterally on the thigh near the patella and proximolaterally. B: For ADF, the electrodes were placed on the muscle belly of the tibialis anterior and halfway down the shank. For both KE and ADF three EMG electrodes were placed on a line between the stimulation electrodes. The patella is outlined with a circle and the head of the fibula is marked with a cross.

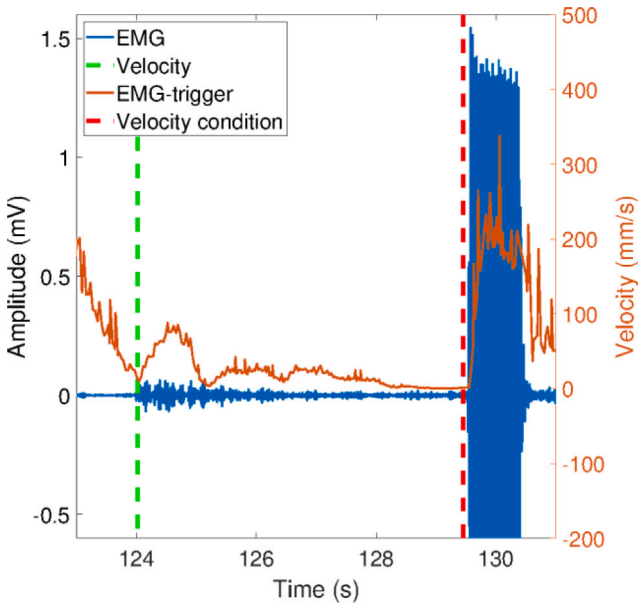

Fig. 5. The recorded EMG and velocity during a single knee extension (KE) repetition of the *Trig* state resulting in subsequent delivery of FES. The 'EMG' is the filtered EMG during the exercise repetition, and the 'Velocity' is the velocity of the end effector. The 'EMG trigger' refers to the time when an EMG trigger was detected. The 'Velocity condition' refers to the time when the velocity had remained below 20 mm/s for 2 s (see Section 2.3), thereby triggering FES (after an EMG trigger was detected).

the robot regardless of their dominant side. Patients used their most affected leg.

To obtain KE using FES, the anode (8 × 13 cm) was placed approximately 3 cm from the patella and centered on the mediolateral aspect of the thigh [44,45]. The cathode (8 × 13 cm) was placed as proximal as possible on the thigh, with the electrode's medial side aligned with the center of the anode to activate the rectus femoris and vastus lateralis muscles (Fig. 4A) [44,45]. To generate ADF, the cathode (3.2 cm diameter) was placed on the muscle belly of the tibialis anterior, approximately 5 cm distal to the head of the fibula, and close to the tibia [45,46]. The anode (4 × 6 cm) was placed halfway between the head of the fibula and the lateral malleolus with the shorter medial side close to the tibia (Fig. 4B) [45,46]. For both KE and ADF, the oval electrodes were positioned with the shorter side parallel to the muscle fibers.

Three EMG electrodes were placed in sequence approximately in the middle between the stimulation electrodes relevant to the exercise, with the center electrode serving as the reference in able-bodied participants (Fig. 4A and B). In stroke patients, the reference electrode was placed on the patella.

After mounting all electrodes, the calibration steps described in Section System calibration were performed. For KE, the desired trajectory started with the participant's or patient's leg at approximately 90 degrees hip and knee flexion and ended with a fully extended leg. For ADF, the desired trajectory started with the participant's or patient's ankle as extended as comfortably possible and ended with their ankle as flexed as comfortably possible.

2.4.3. Technical validation

The experiment consisted of a single session lasting approximately two hours per participant.

The able-bodied participants were informed that the four different states (*Vol*, *Trig*, *Auto*, and *Mech*) would be tested and in which order. The participants were asked to adopt a behavior that would trigger the state transitions necessary to end in the target state. Each state was tested a total of 20 times in bouts of five repetitions across four trials in a randomized order (see randomization scheme in Fig. 6), using the following procedure:

- *Vol*: Participants were not instructed on how to exercise, other than they should be using their own voluntary effort as they felt natural.
- *Trig*: Participants were asked to produce a small movement (KE/ADF) or contraction to generate sufficient EMG to activate the EMG trigger and then relax. Such behavior activated the transition from *Vol* to *Trig* state, which resulted in the administration of FES. See an example of the EMG and velocity during an activation of the *Trig* state in Fig. 5.
- *Auto*: Participants were instructed to relax. Eventually, the 10-s time limit for detecting the EMG trigger was exceeded triggering the *Auto* state and the administration of FES.
- *Mech*: Participants were asked to relax (same as *Auto*). The stimulator was turned off, and therefore although the FES was "activated" when the system progressed into *Auto* state, the stimulation was not delivered, and no movement was generated. Eventually, this led to the triggering of mechanical assistance.

After completing 20 repetitions of each state for KE, the same procedure was repeated for the ADF exercise.

2.4.4. Clinical feasibility test

The clinical feasibility test consisted of a single session per patient. The session lasted approximately 2.5 h.

During the session, the patients performed up to 20 repetitions (depending on their capability) of active movements without any assistance to assess their status. Subsequently, two trials of up to 30 repetitions of both KE and ADF were administered with the state machine active. The patients were instructed to exercise using their own efforts without advising them to adopt any specific behavior. Hence, every change in the state of the system was due to the changes in the patients' capability.

Following each trial of 30 repetitions, the patients were asked to rate how fatigued they felt after exercising with the system. They used a VAS scale from 0–10 with "0" corresponding to "not fatigued at all" and "10" corresponding to "the most fatigued imaginable".

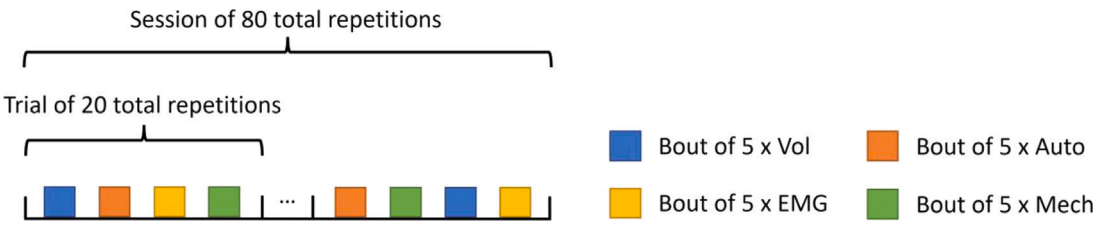

Fig. 6. Overview of randomization of state targets during the technical validation. Each colored block corresponds to five repetitions of a specific state. Each trial consisted of four blocks (20 repetitions) and the whole session consisted of four trials for KE and four for ADF (80 repetitions each, 20 per state).

2.4.5. Outcome measures

During the two experiments, data were continuously recorded by the system. The collected data comprised the AAN state transitions for each repetition, the EMG signals, the velocity of the end effector, and the timestamps for state transitions.

The main outcome of the technical validation was the accuracy of the AAN state machine in correctly transitioning to the target state. The accuracy of the AAN state machine was obtained by comparing the target state instructed to the participants with the final state achieved by the system at the end of the repetition and calculating the percentage of matches. As explained in the Section AAN state machine the AAN state machine was programmed to be progressive in terms of support. Therefore, only the final state was considered when calculating the accuracy. In addition, the sensitivity and precision of transitions were calculated for each state. The sensitivity was calculated as: $TP/(TP + FN)$ where TP indicates true positives and FN false negatives of a given state. The precision was calculated as: $TP/(TP+FP)$ where FP denotes false positives of a given state.

In the clinical feasibility test, the main outcome was the progression of the AAN states. The values 1 to 4 were assigned to *Vol*, *Trig*, *Auto*, and *Mech* states, respectively, to visually represent the states of each exercise repetition.

The secondary outcomes during the technical validation were the number of identified EMG triggers in each state, the onset of FES and mechanical assistance relative to the expected onsets (as defined in Fig. 3), and the completion time of a repetition in each state.

The detection of EMG triggers was investigated in an offline analysis by applying the EMG trigger detection algorithm to all EMG data recorded at each exercise repetition. A percentage of completed exercise repetitions containing detected EMG triggers could then be calculated for each AAN state. EMG triggers were expected during all *Vol* and prior to all *Trig* state repetitions as these involved complete or partial voluntary effort. No triggers were expected prior to or during the *Auto* and *Mech* states as participants should be relaxing according to the instructions given (see Section Technical validation).

The onset of FES was calculated as the time when the system started the delivery of FES relative to the last time the velocity was higher or equal to the velocity threshold. If an EMG trigger was detected, only the velocity samples after the EMG trigger counted toward the onset of FES. The onset of mechanical assistance was calculated as the time elapsed between the FES onset and the time when the mechanical assistance was provided. Ideally, the onset of FES would be 2 or 10 s (in the *Trig* or *Auto* state, respectively), while the onset of mechanical assistance would be 2 s.

The completion time of each exercise repetition was calculated as the time from the start of one exercise repetition to the start of the next repetition.

In the clinical feasibility test, the secondary outcome was the average fatigue score.

The aforementioned analyses were completed for both KE and ADF exercises using MATLAB version R2022b.

All outcome measures are reported as mean ± standard deviation across participants.

3. Results

3.1. Technical validation

3.1.1. Knee extension

On average, able-bodied participants completed 19.9 ± 0.3 repetitions of each state (see Table 2). The state machine accuracy for transitioning between the states was 97.2 ± 2.2% during the KE exercise. The specific state transition rates are shown in Fig. 7 and the sensitivity and precision of each state transition are shown in Table 2.

The sensitivity and precision of transitions into each state was more than 90%. *Mech* had the overall highest sensitivity and precision and *Auto* had the lowest. The most common error was the activation of the *Trig* state instead of *Auto*, which occurred 18 times (9.0%), while other misclassifications were rare, i.e., ≤ 2 times (1%).

The EMG trigger detection rate, the onset of FES and mechanical assistance, and the completion time of exercise repetitions in all states during the KE exercise are reported in Table 2.

As shown in Table 2, EMG triggers were detected during 62.0 ± 39.9% of the *Vol* state repetitions, indicating a high variability between subjects. On the other hand, 100.0 ± 0.0% of *Trig* state repetitions were preceded by an EMG trigger. During 0.5 ± 1.7% of the *Auto* state repetitions (a single occurrence) an EMG trigger was produced, while 3.0 ± 4.2% of the *Mech* repetitions (six occurrences) were preceded by an EMG trigger.

The onset of FES was 2.05 ± 0.02 s for *Trig* and 10.02 ± 0.00 s for *Auto*, while the onset of mechanical assistance was 2.10 ± 0.01 s. These were consistent with the completion times for a repetition in each state during KE, ranging from 7.09 s during *Vol* to 19.48 during *Mech* preceded by *Auto*. The completion time increased across the states in the following order: *Vol*, *Trig*, *Mech* preceded by *Trig*, *Auto*, and *Mech* preceded by *Auto*. This correctly reflects the onset time of FES and mechanical assistance and how these relate to each state.

3.1.2. Ankle dorsal flexion

One subject did not complete the ADF exercise due to discomfort during electrical stimulation. The remaining subjects completed 19.8 ± 0.7 repetitions of each state (see Table 3). The accuracy of the state machine for transitioning between states was 96.6 ± 5.3%. The specific state transition rates for each state are shown in Fig. 7 and the sensitivity and precision characterizing each state are shown in Table 3.

The achieved sensitivity and precision were higher than 90%. As in KE, the highest sensitivity and precision were obtained for *Mech* and the lowest for *Trig*. Likewise, the most common error was the transition into *Trig* instead of *Auto*, which occurred 14 times (7.8%). Other misclassifications were rare, i.e., ≤ 6 times (3.5%). The EMG trigger detection rate, the onset of FES and mechanical assistance, and the completion time of exercise repetitions in all states during the ADF exercise are reported in Table 3.

EMG triggers were detected in all *Vol* and *Trig* repetitions, none was detected in *Auto*, and 12.4 ± 23.2% were detected in *Mech* (20 occurrences).

The onset of FES was 2.01 ± 0.01 s for *Trig*, 10.02 ± 0.00 s for *Auto*, and 2.10 ± 0.02 for *Mech*. These were also consistent with the

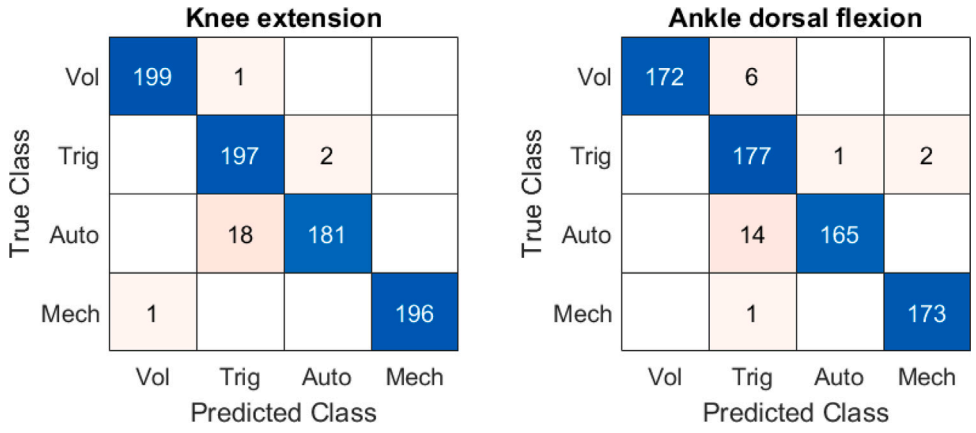

Fig. 7. Confusion matrix for transitioning between the different AAN states during KE and ADF exercises (healthy participants).

Table 2
The system outcome measures during KE per state. Repetitions: the number of completed repetitions per participant. EMG trigger: the percentage of repetitions during which EMG triggers were detected. Onset: The onset of FES or mechanical assistance. Time: The time to complete an entire exercise repetition.

	Repetitions	Sensitivity (%)	Precision (%)	EMG trigger (%)	Onset (s)	Time (s)
Vol	20.0 ± 0.0	99.5 ± 1.6	99.5 ± 1.6	62.0 ± 39.9	–	7.09 ± 0.39
Trig	19.9 ± 0.3	99.0 ± 3.2	91.3 ± 4.9	100.0 ± 0.0	2.05 ± 0.02^{F}	11.25 ± 0.94
Auto	19.9 ± 0.3	91.0 ± 5.2	99.0 ± 3.3	0.5 ± 1.7	10.02 ± 0.00^{F}	15.59 ± 0.52
Mech	19.7 ± 0.5	99.5 ± 1.7	100.0 ± 0.0	3.0 ± 4.2	2.10 ± 0.01^{M}	15.25 ± 2.05^{PT}
						19.48 ± 0.74^{PA}

F — Onset of FES administration.
M — Onset of mechanical assistance.
PT — Cases where *Mech* was preceded by *Trig* (190 cases).
PA — Cases where *Mech* was preceded by *Auto* (6 cases).

Table 3
The system outcome measures during ADF per state. Repetitions: the number of completed repetitions per participant. EMG trigger: the percentage of repetitions during which EMG triggers were detected. Onset: The onset of FES or mechanical assistance. Time: The time to complete an entire exercise repetition.

	Repetitions	Sensitivity (%)	Precision (%)	EMG trigger (%)	Onset (s)	Time (s)
Vol	19.8 ± 0.7	96.5 ± 6.0	100.0 ± 0.0	100.0 ± 0.0	–	3.60 ± 0.62
Trig	20.0 ± 0.0	98.3 ± 2.5	91.1 ± 12.2	100.0 ± 0.0	2.01 ± 0.01^{F}	6.43 ± 0.93
Auto	19.9 ± 0.3	92.2 ± 12.5	99.5 ± 1.6	0.0 ± 0.0	10.02 ± 0.00^{F}	12.44 ± 0.40
Mech	19.3 ± 1.1	99.4 ± 1.9	98.9 ± 2.3	12.4 ± 23.2	2.10 ± 0.02^{M}	9.35 ± 1.87^{PT}
						16.18 ± 1.27^{PA}

F — Onset of FES administration.
M — Onset of mechanical assistance.
PT — Cases where *Mech* was preceded by *Trig* (153 cases).
PA — Cases where *Mech* was preceded by *Auto* (20 cases).

completion times of a repetition in each state during ADF, ranging from 3.6 s during *Vol* to 16.18 s during *Mech* when preceded by *Auto*. With respect to the completion time, the order of the states was the same as for KE.

3.2. Clinical feasibility test

3.2.1. Progression of states

The number of repetitions in each state for each patient during KE and ADF is shown in Table 4 and the progression of states across repetitions of the KE and ADF exercise for the two stroke patients is shown in Fig. 8. During ADF exercise patient 2 had a reduction in the EMG trigger threshold of 20%, beginning at repetition 10.

The states of the AAN system, and thereby the support provided by the system, varied between the two patients and between the two exercises. All states but *Mech* were triggered by patient 1, whereas all states were triggered during ADF by patient 2. The physical capability was quite stable during both exercises for patient 1 and during KE for patient 2. Both patients were able to perform KE exercises using voluntary efforts, and the system did not need to deliver assistance as the state machine was in the *Vol* state consistently across the repetitions. However, ADF was more challenging, and *Trig* was the most prevalent state for patient 1. Furthermore, patient 1 exhibited a slight increase in the prevalence of the *Auto* state during ADF (one occurrence in the first 30 repetitions versus six in the final 30 repetitions). During ADF, the pattern of triggered states for patient 2 indicated a decreasing need for support during the exercise. Initially, the patient triggered all assistance levels, whereas after approx. 20 repetitions, the state machine consistently remained in the *Vol* state and the system did not need to deliver assistance.

Table 4
Overview of the patients' performance during the clinical feasibility test. Rep: Repetitions of exercise in KE/ADF. *Vol*, *Trig*, *Auto*, *Mech*: Number of repetitions completed in the *Vol*, *Trig*, *Auto*, *Mech* state during KE/ADF, respectively. Fat. KE, Fat. ADF: Ratings of fatigue in trial 1/trial 2 of KE and ADF, respectively.

	Rep.	*Vol*	*Trig*	*Auto*	*Mech*	Fat. KE	Fat. ADF
Patient 1	60/60	57/4	2/49	1/7	0/0	2/2	4/4
Patient 2	60/60	60/43	0/5	0/9	0/3	2/2	5/6

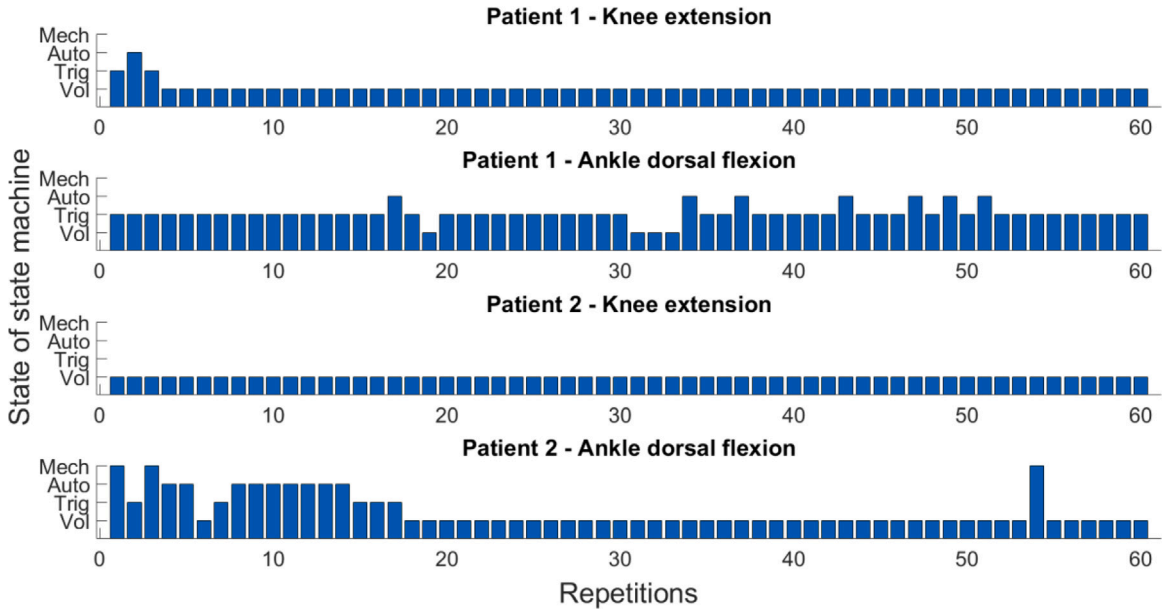

Fig. 8. The support provided by the system during each repetition of KE and ADF for the two stroke patients.

3.2.2. Fatigue

The fatigue scores reported by the patients following the KE and ADF exercises are reported in Table 4.

For KE, both patients rated the fatigue score at 2.0 ± 0.0, while ADF was rated at 4.0 ± 0.0 by patient 1 and 5.5 ± 0.7 by patient 2. Thus, patient 2 reported a fatigue score 1.5 higher than patient 1 during ADF. Note that patient 1 received three times more support compared with patient 2 (56 repetitions vs. 17 repetitions as seen in Table 4 and Fig. 8).

4. Discussion

In this study, we presented a novel hybrid system for the rehabilitation of the lower limbs which further expands the framework introduced by Petersen et al. 2020 [38]. The novel system was comprised of the robotic manipulator ROBERT®, an EMG triggered FES system, and a state machine implementing AAN control. The system implements an approach to AAN that is simple, yet capable of adjusting the support to the users' capabilities. The system demonstrates how different modalities of support, i.e., FES and mechanical assistance, may work in tandem without the necessity of complex algorithms for adjusting the levels of support provided by each modality individually. This simple approach to combining FES and mechanical assistance during exercise also decreases the required calibration times that often accompany systems based on more complex algorithms [39,47].

The system used in this study differs from that used by Petersen et al. 2020, which relied on an EMG trigger to administer FES without further consideration of whether the patients were expectedly able to exercise on their own or not [38]. The developed AAN paradigm combined different assistance modalities to allow patients to exercise by exploiting their own capabilities and without unnecessary external support, which is suggested to facilitate motor learning and lead to greater rehabilitative outcomes [22,23,27,28]. The present study established the technical and preliminary clinical feasibility of the system while its rehabilitative potential will be investigated in future clinical studies.

Similar to the work by Yang et al. 2023, the AAN paradigm implemented in the present study was designed as a state machine with four distinct states [39]. While the system by Yang et al. 2023, changed states depending on the trajectory error of the performed movement [39], the present system changed states depending on the assessment of active participation of the participant by monitoring EMG activity (EMG trigger) and the movement velocity. The decision to focus on engagement was motivated by the fact that some trajectory errors may be beneficial to facilitate reinforced learning [22,23,48]. Hence, the present system selected the assistance level to the minimum required for the participant to be able to complete the exercise (maintaining velocity). Additionally, the system states by Yang et al. 2023 imposed four modes of force provided by the robotic system: robot-resist, free mode, robot-assistive, or robot-dominant [39]. The present system implemented only two equivalent modes of force for the robot: robot-resist (during *Vol*, *Trig*, and *Auto*, where the robot resists the movement of the participant) and robot-dominant (during *Mech*, where the robot takes control and moves the leg of the participant). This was possible because a second support modality (FES) was available in the present system. Therefore, the robot could always exert resistive force on the participants' muscles as the FES would support the participants in completing the exercise, even if their voluntary efforts were insufficient (during *Trig* and *Auto*). Hence, active support was only provided by the robot during the *Mech* state, when the AAN state machine determined that the effort by a participant alone or combined with FES was insufficient.

Post calibration the individualized FES amplitudes were not updated, although participants' responses to the FES could change over time. Leerskov et al. 2022, found that mean force and velocity produced in response to FES delivered while exercising in a hybrid FES-robotic system, could change following 50 successive repetitions in the range −4.5 to 7.9% (force) and −22.3 to 18.6% (velocity) [40]. This suggests that future versions of the system may require a continuous evaluation of the responses to FES during use. However, in the present study, there was little indication that adjustments of the FES amplitude were necessary.

The results of the technical validation showed that the system correctly identified the behavior executed by the able-bodied volunteers to generate the transition into the target state of the system with a high accuracy of 96.6–97.3%. This suggests that the system was properly implemented to detect the desired behaviors and thereby apply the appropriate level of support (no support, FES only, or FES and mechanical assistance).

Overall, the AAN system exhibited high sensitivity and precision (>90%). The most common error was the transition into *Trig* when the target was *Auto* due to the detection of "false" EMG triggers. At the end of a repetition, the robot guided the leg/ankle of the participant back into the starting position. Once there, the position controller was deactivated while the resistance opposing the exercise trajectory was turned on. This switch occasionally led to a small drop in the participant's leg position (approximately 5 cm). Based on the observations of the experimenter, this drop could induce a response in the leg that produced enough EMG activity to trigger the system at the beginning of an exercise repetition. Petersen et al. 2020 reported that 20.5% and 15.5% of the EMG triggers for KE and ADF, respectively, were premature and produced by noise, suggesting that they may have faced a similar issue [38]. The number of premature triggers in Petersen et al. 2020 is twice the number of errors in the *Auto* state (15.5–20.5% versus 7.8–9.0%), which comprises noise and unintended triggers suggesting that the issue was smaller in the present study. Hence, the EMG trigger calculation method introduced in this study to mitigate the issue of premature noise-driven triggers was partly successful. Some trigger errors were additionally caused due to unintentionally generated EMG activity. The errors occurred as participants did not relax sufficiently while the robot moved their leg to the start position, thereby producing an EMG trigger immediately when the next repetition started. Finally, the participants occasionally made mistakes and moved when they were supposed to lie still (e.g., during testing of the *Auto* state) due to lack of focus or misunderstanding of the instructions. However, such mistakes were not considered an error in the system as the AAN state machine acted appropriately to the input provided although the input was unintended in the test.

In addition, EMG triggers were occasionally not detected when they were supposed to be generated. For instance, only 62% of *Vol* repetitions during KE resulted in EMG trigger detection although 100% was expected as this state involved the most muscular activity. The subjects were able to complete the exercise repetition while remaining in the *Vol* state as they completed the repetition before the timer activated the *Auto* state. Further inspection of the data revealed that five participants had difficulties in producing triggers during the testing of the *Vol* state, and collectively accounted for 37.5% of the missing triggers. This was likely caused by the participants not relaxing properly during calibration as four out of the five participants had the highest recorded thresholds, across all participants. It is also possible that these participants produced the desired trajectory by relying on the gluteus maximus (hip extension) more than the quadriceps [49], thereby generating less EMG activity in the monitored muscles. The participants were not instructed how to move during the testing of the *Vol* state but were simply told to produce the movement 'naturally'. However, when testing the *Trig* state, they were instructed specifically to focus on knee extension resulting in EMG triggers being identified in 99% of the *Trig* repetitions despite the low detection rate when testing the *Vol* state. This indicates that the changed movement strategy produced sufficient EMG for exceeding the EMG trigger threshold. Further, it partly suggests that a high EMG trigger threshold and/or a movement strategy favoring muscles that were not monitored is what caused the absence of EMG triggers. Finally, the difference in the ability to produce EMG triggers could be caused by individual differences in the tissue composition as the amount of adipose tissue under the recording electrodes affects the amplitude of the recorded EMG [50]. To avoid the challenges in EMG trigger detection, the version of the system used in the clinical feasibility test had the option of manually adjusting the EMG trigger threshold in cases where triggers were not produced appropriately. This, however, was only relevant for patient 2 during ADF. Further improvement could be made by introducing a blanking method, which would ignore the EMG during the switch at the beginning of an exercise repetition, which could produce false triggers. Furthermore, as with the FES-amplitude, the EMG-trigger thresholds validity was not reassessed during online use in the technical validation. Recalibrating or adjusting the EMG-trigger could potentially have reduced the prevalence of missing EMG-triggers. Finally, a possibility would be to place EMG electrodes on more muscles (e.g., gluteus maximus), but this would increase the system setup and calibration time which may decrease its clinical applicability.

The onsets of FES and mechanical assistance obtained in the technical validation during both KE and ADF suggest close compliance with the specifications of the AAN state machine (Fig. 3). Additionally, the completion time of repetitions in each state followed the expected order and allows for a number of repetitions of KE and ADF in the range of 184–507 and 222–1000, respectively, during one hour of uninterrupted exercising. This is within the range required for promoting neural change, although in the low end [51]. However, as the system targets severely affected patients, who may have limited alternatives to exercise, the immediate goal of the system is to enable the patients to receive simple yet demanding training while alternative options are limited.

In the clinical feasibility test, it was expected that the patients exercising with the system would be as actively involved as allowed by their physical capabilities while receiving the minimum required support. This is indeed supported by the states activated during the exercises (Fig. 8). Patient 1 required consistent FES support during ADF and patient 2 required gradually reduced support. This indicates that the system was able to adapt to the support required by the patient, which is in line with the principles identified by Maier et al. 2019 [13]. Further, these results support the potential feasibility of using the system with patients in a rehabilitative setting.

Both patients were able to perform the KE using voluntary efforts. This was correctly detected by the system which remained in the *Vol* state and did not provide support. However, this was surprising for patient 1 as a Motricity Index of 0 was established at recruitment. We believe that the gravity compensation provided by the system and the supine exercising position were enough to allow for the emergence of volitional movement. Although unexpected, this is an encouraging result implying that sometimes even a simple intervention and minimal support can substantially improve the patient's ability to move and exercise. However, patient 1 still needed active support during ADF, which was expected considering the low Motricity Index of the patient. Another unexpected result was that patient 2 decreased the need for support while performing ADF, particularly as it was deemed necessary to reduce the EMG trigger threshold, just prior to the increased performance. This may be due to different reasons. The patient may have become more familiar with the system functioning after a few repetitions, the first repetitions may have provided the required muscle warm-up [52], or the patient may have become more motivated and engaged [52] and after that was able to continue without support. Finally, the reduced need for support may be caused by potentiation following repeated administration of FES similar to what was observed in Leerskov et al. 2022 in able-bodied individuals, who exercised with a comparable rehabilitation system [40].

The patients rated the fatigue due to exercising with the system at 2 and 4.75 out of 10 for KE and ADF, respectively, indicating that both patients were more fatigued during ADF. This is reflected in the increased need for support in ADF relative to KE for both patients. Additionally, patient 2 rated the fatigue during ADF higher than patient 1, which is consistent with the fact that patient 2 exercised mostly using their own efforts (*Vol*) and utilizing more of their own resources, whereas patient 1 primarily received support (*Trig*). Overall, the fatigue scores indicate that exercising with the system has the capacity to provide an exertive exercise that is not too exhaustive. For KE, it may be necessary to provide additional repetitions or a larger resistance to observe more fatigue. Generally, more repetitions than were administered in the present study are indeed required to reach levels necessary to induce neural changes [51]. However, the reduced need for support in ADF for patient 2, from their 18th repetition, and a fatigue rating of 5/6, could indicate that the developed system

facilitated a substantial use of the patient's own resources, which is important for recovery [22,23,27,28].

5. Conclusion

In this paper we have introduced a novel hybrid rehabilitation system utilizing a simple yet effective AAN strategy for lower limb rehabilitation of bedridden stroke patients. The tests demonstrated that the system detected the capability of the patients and adjusted the level of support to the minimum required while providing an exertive exercise. This ensured a high degree of active participation from patients, which is important to promote their recovery. Thus, we demonstrated the preliminary feasibility of using the system in stroke patients.

The study shows that AAN can be implemented in an additive design, i.e., adding FES or FES and mechanical assistance, as discrete levels of support. This design does not require the calibration of complex algorithms for managing the contribution of the different subsystems. Calibration can be time-consuming, which is of great importance as there is often limited time available for patients to exercise.

The present system provides a therapy option for severely affected stroke patients, who can benefit from it even while still bedridden. The system may relieve therapists from administering strenuous manual therapy while simultaneously ensuring that patients receive high-quality exercising.

5.1. Limitations

The specific thresholds for time and velocity utilized in the clinical feasibility test were obtained in pilot studies on three stroke patients and are thus not validated systematically for varying degrees of disability. Therefore, similarly to the manual adjustment of the EMG-trigger threshold, it should be possible to adjust these thresholds manually in future versions of the system.

The clinical feasibility test of the system involved only two patients. Hence, the tendencies highlighted in the present paper should be verified and should be considered preliminary. A more extensive clinical feasibility test is underway which may more appropriately conclude the feasibility of the present system for use in stroke rehabilitation.

The developed system utilized an additive support design, where no support, FES, and FES plus mechanical assistance comprised the three levels of support in the system. Some patients may require more support than FES provides in the current design, but less than what is provided when adding mechanical assistance. Hence, more discrete levels of support could be beneficial for these patients.

The AAN control system implemented in the present study did not include methods for detecting involuntary movements, although a "safe mode" and emergency stops were in place. In future versions of the system, this is a point of improvement. During the study, the experimenter was always observing participants, and at no point during the study were the emergency stops used. However, it should be noted that frequent spasms and pronounced spasticity, particularly in the presence of FES, could be a contraindication for using the proposed system. Both spasms and pronounced spasticity may lead to interruptions in the exercise, which, if too excessive, may prevent the patient from reaching a beneficial amount of exercise using the proposed system.

Previous studies have suggested that hybrid robotic-FES rehabilitation is effective [53–55], and it is hypothesized that AAN may improve this efficiency. However, as the present study investigated the feasibility of using the developed system and only involved single sessions, no measures of therapy effectiveness were included. Hence, the effect of exercise with the developed AAN system, relative to existing alternatives remains unknown and should be tested in future clinical studies.

5.2. Future work

Future work should include the assessment of the rehabilitative capability of the system in more stroke patients and over an extended period of time.

Additionally, no comparison was made between the present system and that of a purely mechanical or a purely FES-based system. This comparison would underline whether the present system would allow for a prolonged exercise session for stroke patients and should be pursued in future studies.

Future studies should investigate improving the assist-as-needed aspect of the present system, e.g., by grading the pulse width of the FES or the force provided by the mechanical assistance to limit the support to the strictly necessary level. This may further improve the active engagement of users of the system and prolong the onset of fatigue caused by repeated application of FES.

Gamification of rehabilitation has previously been shown to an effective way to improve motivation and adherence to exercise [56,57]. Due to the various sensors involved in the present system, there is rich opportunity to gamify the performed exercise, to get a more immersive exercise experience, that potentially offers greater outcomes compared to the current non-gamified version of the system. This would be interesting to investigate in future studies.

Finally, the developed system may have application in other severely affected neurological groups. Future studies should investigate the applicability of the developed system in those groups, e.g., spinal cord injury, to explore the scalability of the system.

CRediT authorship contribution statement

Kasper S. Leerskov: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Cindy J.H. Rikhof:** Writing – original draft, Validation, Resources, Methodology, Investigation, Data curation, Conceptualization. **Erika G. Spaich:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Project administration, Methodology, Funding acquisition, Conceptualization. **Strahinja Dosen:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Project administration, Methodology, Funding acquisition, Conceptualization. **Gerdienke B. Prange-Lasonder:** Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Erik C. Prinsen:** Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization. **Johan S. Rietman:** Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization. **Lotte N.S. Andreasen Struijk:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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- Kasper S. Leerskov was a part-time consultant of Life Science Robotics ApS.

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Kasper S. Leerskov is a part-time consultant of Life Science Robotics ApS.

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