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Effectiveness of Ankle-Foot Orthoses for Patients with Weakness of the Plantarflexors and Dorsiflexors: Biomechanical Comparison of Different Orthotic Concepts

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ABSTRACT

Introduction: Weakness of plantarflexor and dorsiflexor muscles is a complex individual condition and can result in pathological gait, such as crouch gait or knee hyperextension. Affected patients can be supported with ankle-foot orthoses (AFOs) to improve gait and safety.

Objective: This study aims to compare three orthotic ankle joint designs in AFOs for patients with muscle weakness in the plantarflexors and/or dorsiflexors: a conventional hinged ankle joint with rigid stops (CAJ), a jointless orthosis (JLO), and a reactive-dynamic ankle joint with adjustable spring modules (RDA).

Study Design: Seven patients with plantarflexor and/or dorsiflexor muscle weakness tested three orthosis configurations in randomized order during a single session.

Methods: Biomechanical gait analysis was performed during standing and walking on level ground and up and down 10° slopes. The main outcomes were ground reaction forces, joint angles, moments, and power at the ankle, knee, and hip joints. Mean values of outcome measures for patients and values of an able-bodied control group were compared with nonparametric analyses of variance and pairwise post hoc tests.

Results: Throughout all motion tasks, statistically significant differences ($P < 0.05$) were predominantly found in ankle and knee joint kinematics between RDA and CAJ, as well as between JLO and CAJ, whereas only few differences were found between RDA and JLO.

Conclusions: For this patient group, RDA enabled the most physiological gait, with outcomes measure values closest to those of the able-bodied control group, and the best perception of support for an active lifestyle and physically demanding activities. In less physically demanding situations, such as short walking distances and even surfaces, JLO also showed sufficient support for physiological gait and may be an adequate orthosis for patients living with supportive infrastructure or a more sedentary lifestyle. CAJ restricted physiological movements, showed the highest deviations from the values of the able-bodied controls in most activities, and provides the least comfort for patients in the tested situations.

Clinical Relevance Statement: Determining the best possible orthotic care and support for different patient groups is essential to enable independence, safety, and comfort during activities of daily living based on individual requirements.
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KEY INDEXING TERMS: ankle-foot orthosis, orthotic ankle joint, orthotic care, neurological lower-leg pathologies, muscle weakness, biomechanics, joint kinematics

INTRODUCTION

Neurological conditions, such as multiple sclerosis, poliomyelitis, stroke, or disc herniation with nerve root compression, often result in muscle weakness or paralysis in various regions of the body. Complex weakness of the shank muscles affects plantarflexion and/or dorsiflexion in the ankle joint and may, therefore, cause

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serious functional impairment in patients during simple activities of daily living (ADLs), such as standing and walking. Compensatory movements and mobility limitations may be reduced or even avoided with suitable orthotic care. Patients affected by such complex weakness, in contrast to an isolated tibial muscle weakness resulting in simple foot drop, are typically fitted with an ankle-foot orthosis (AFO) incorporating a ventral support pad at the tibia and an ankle-supporting joint system, enabling a compromise among control, movement, and functionality of both the knee and ankle joint.[1–4] Common support mechanisms use individually shaped and partially flexible carbon fiber or thermoplastic shells, fastened by straps just below the knee joint, and either no joint system or orthotic ankle joint systems enabling plantarflexion and dorsiflexion between fixed joint stops.[1–4] These allow safe and controlled standing and walking on level ground for most patients.[5–8] However, orthotic ankle joints with a small range of motion (ROM) and rigid stops limit physiological movement not only in the ankle but also in the knee joint, therefore affecting the entire gait cycle.[5–7,9–12] Especially on uneven surfaces or slopes, small adaptations to maintain balance, usually fulfilled by the shank muscles, cannot take place, often resulting in serious compensatory movement patterns and posture adaptations as well as unnatural strain to the ankle, knee, and hip joints.[13] Furthermore, affected patients often report premature fatigue during ADLs.[14,15]

Over the pasts few years of orthosis development, these problems have been addressed using increased ROM for both dorsiflexion and plantarflexion and individually adjustable motion resistance by specifically designed energy-storing-and-returning spring modules implemented in orthotic ankle joints. Because of this enhanced functionality, these ankles may be referred to as "reactive-dynamic ankle" (RDA). The most common joints of that type are the NEURO SWING (Fior & Gentz, Germany), the Triple Action (Becker Orthopedics, USA), and the Nexgear Tango (Ottobock, Germany). The effects and the patient benefits that can be expected from this new orthotic ankle joint generation have been observed and confirmed in a small number of scientific studies.[2,16–18] In the present study, the potential of RDA-AFOs was systematically compared with two established AFO designs that, until now, have been the standard of care for AFOs for patients with weakness or partial paralysis of their shank muscles, in order to evaluate whether the RDA-AFO may provide better care for this patient group.

METHODS

PATIENTS

Seven patients (6 male, 1 female) with a mean age of 57 ± 15 years, height 185 ± 10 cm, and body weight 91 ± 17 kg were included in this study. Patients were recruited from the Ottobock Care Unit in Göttingen, whereby the inclusion criteria was the prescription of an AFO by a doctor, due to a neurological condition causing decreased plantarflexor and/or dorsiflexor muscle strength (rated 4 or lower according to the manual muscle function test of Janda[19]) in one (unilateral, n = 3) or both (bilateral, n = 4) shanks. All patients had been using an RDA-AFOs for 2.4 ± 1.3 years (mean ± standard deviation) and had experience with other AFO systems from previous care settings, including carbon fiber nonarticulated AFO systems. Patients were included if able to walk with their RDA and without further assistance for at least 15 m multiple times with short breaks. Patients were excluded if they had other orthopedic or spasticity-related handicaps severely influencing gait and posture. Further exclusion criteria were not specified in order to acquire a representative group of participants; however, this may have led to variability in the recorded data (see study limitations). Details on the demographics and pathologies are presented in Tables 1 and 2. Before study inclusion, all patients provided written informed consent. The study was approved by the Ethics Committee of the Universitätsmedizin Göttingen.

STUDY DESIGN

For the study, patients tested three different AFO configurations, as well as a control situation without an orthosis, in randomized order during a single session with sufficient breaks for recovery and familiarization (minimum 15 minutes). All orthoses were individually fitted by a certified orthotist using the L.A.S.A.R. posture system (Otto Bock HealthCare, Duderstadt, Germany) to optimize orthotic alignment in footwear, according to previously established protocols.[12,20] All patients wore their own footwear (similar, sturdy loafers) to ensure the patients' usual and representative gait. The test situations comprised standing and walking on level ground as well as up and down a 5-m ramp with a slope of 10°. To evaluate patient-reported effectiveness, comfort, safety, and support of the different orthoses, patients were asked to fill in detailed questionnaires directly after testing.

ORTHOSES MODELS

Reactive-Dynamic Ankle Joint System (Nexgear Tango)

The Nexgear Tango ankle joint (Otto Bock HealthCare, Duderstadt, Germany) is a modular orthotic ankle system with individually adjustable and reactive coil spring modules to control resistance and ROM during dorsiflexion and plantarflexion ("reactive-dynamic ankle joint system," RDA, Figure 1). Because of the modular design, the joint can also be configured to act as a conventional ankle joint system with an ROM limited by rigid dorsiflexion and plantarflexion stops. This configuration was used

Table 1. Demographic patient data

Patient no.	Age [y]	Height [m]	Weight [kg]	Gender	Affected side
1	78	1.78	89.0	Male	Bilateral
2	50	2.00	94.0	Male	Bilateral
3	49	1.86	124.0	Male	Right
4	61	1.94	83.0	Male	Right
5	75	1.81	80.0	Male	Bilateral
6	30	1.68	72.0	Female	Bilateral
7	56	1.90	95.0	Male	Left
Mean	57	1.85	91.0		
SD	15.2	0.1	15.4		

Table 2. Underlying clinical conditions and lower limb muscle strength according to Janda's manual muscle test

ID no.	Clinical condition	Hip extensors Left	Hip extensors Right	Hip flexors Left	Hip flexors Right	Knee extensors Left	Knee extensors Right	Knee flexors Left	Knee flexors Right	Plantarflexors Left	Plantarflexors Right	Dorsiflexors Left	Dorsiflexors Right
1	Polyneuropathy	5	5	5	5	5	5	4	4	3	3	0	0
2	Lower leg paraplegia, plantarflexion weakness	4–5	4	4	4	5	5	4	4	2	2	5	4
3	Hemiparesis post brain hemorrhage (R)	5	4–5	5	5	5	4–	5	5	5	3	5	3
4	Neurological condition post discus prolaps surgery (R)	5	2	5	2	5	3+	5	2+	5	1–2	5	0
5	Condition post spinal canal stenosis	5	4	5	5	5	5	3+	4+	2–	3	2–	3–
6	Condition after diving accident and with rare muscle disease	4–	4	3+	2	3	3	3+	3+	3	3	3	3
7	Condition post L5/S1 discus prolaps surgery (L)	4–	4–	5	5	5	5	5	5	4	5	5	5

for the test situation conventional resistance-free ankle joint system with fixed stops (CAJ). A detailed description of the Nexgear Tango ankle joint was published in an earlier paper.[21]

Jointless Orthosis (JLO; WalkOn Reaction)

The WalkOn Reaction (Otto Bock HealthCare, Duderstadt, Germany) represents a one-piece carbon-fiber orthosis without an adaptable ankle joint system (see Figure 1). The S-shape of the orthosis as well as its material allows flexibility and energy storage and return while bearing weight.[1,2,22] Orthoses displaying this technique of influencing knee motion by transferring forces at the shank and resulting in the named effects have been tested and described as ground reaction or floor reaction AFOs in previous papers.[1,23]

DATA RECORDING AND PROCESSING

Biomechanical gait analysis was performed using a 12-camera 3D-Vicon System (BONITA cams, VICON Motion Systems, Oxford, Great Britain, 200 Hz), coupled with two Kistler Force plates (Type 9287A, KISTLER AG, Wintherthur, Switzerland, 1200 Hz) in the middle of the 12-m walkway or the middle of the 5-m ramp. A self-designed marker set consisting of 17 passive markers was adhered to the skin; this marker set has been used and described in a previous publication.[24] Measurements were conducted using the Vicon Nexus software 2.9.3. Raw data were recorded and reconstructed in 3D, filtered with a Woltring filter (MSE, cutoff frequency 10). Gait parameters were calculated, using self-developed algorithms (Vicon Body Language 3.5), from one valid gait cycle in each trial with a minimum of 5 valid trials per motion task per participant, and included sagittal flexion and extension angles and external moments of the ankle, knee, and hip joints, as well as ankle joint power. Using the Vicon Polygon Software 4.4.6 (VICON Motion Systems, Oxford, Great Britain), all parameters were time-normalized; group mean values, curves, and selected peak values were exported as c3d-data. Further analysis was performed using the MATLAB Software (MATLAB R2022a, The MathWorks Inc, Natick, MA, USA). To capture participants' perception of the orthotic effects in addition to the biomechanical analysis, participants were asked to fill in a short, self-designed questionnaire rating their perception of each orthosis after testing on a scale of 1 ("bad"/debilitating) to 10 ("good"/very helpful) for each motion task. Then participants were asked to rank the three orthoses from 1 (first choice) to 3 (last choice), indicate which one they would choose for each of the motion tasks, and finally mark those motion tasks for which the difference among the three orthoses was particularly significant.

STATISTICAL ANALYSIS

Group means were tested for statistical significance ($P < 0.05$) with the nonparametric Friedman test, as the data were not normally distributed (Shapiro-Wilk test, $P > 0.05$), followed by pairwise Wilcoxon post hoc tests with Bonferroni correction (p_b), and Cohen's d was calculated as an estimate of effect size. Statistical calculations were performed using WinSTAT (Microsoft Excel, Bad Krozingen, Germany). For statistical analysis, all affected body sides were combined (n = 11). Normative values from a previously analyzed able-bodied control group from the Ottobock SE & Co. KGaA database were used for additional comparison. The able-bodied control group was nonmatched and included over 100 participants between 20 and 65 years old (mean age 29 ± 10 years) with no impairments concerning their gait and no other specific exclusion criteria. Additionally, descriptive pattern analysis was performed on the biomechanical parameters, looking for conspicuous differences or abnormalities between group mean curves of the conditions. Bilateral and unilateral patients were evaluated separately. However, no differences were found between the two groups. Participants' perception was analyzed as mean rating scores for each orthosis type during each motion task. Most relevant motion tasks were determined by the percentage of participants who had named these tasks as particularly sensitive for the differences between the tested orthoses.

RESULTS

PATHOLOGICAL GAIT CHARACTERISTICS

When walking without an orthosis, the patients showed highly individual compensatory gait patterns, demonstrated by the sagittal knee joint motion during stance phase (see Figure 2). Two

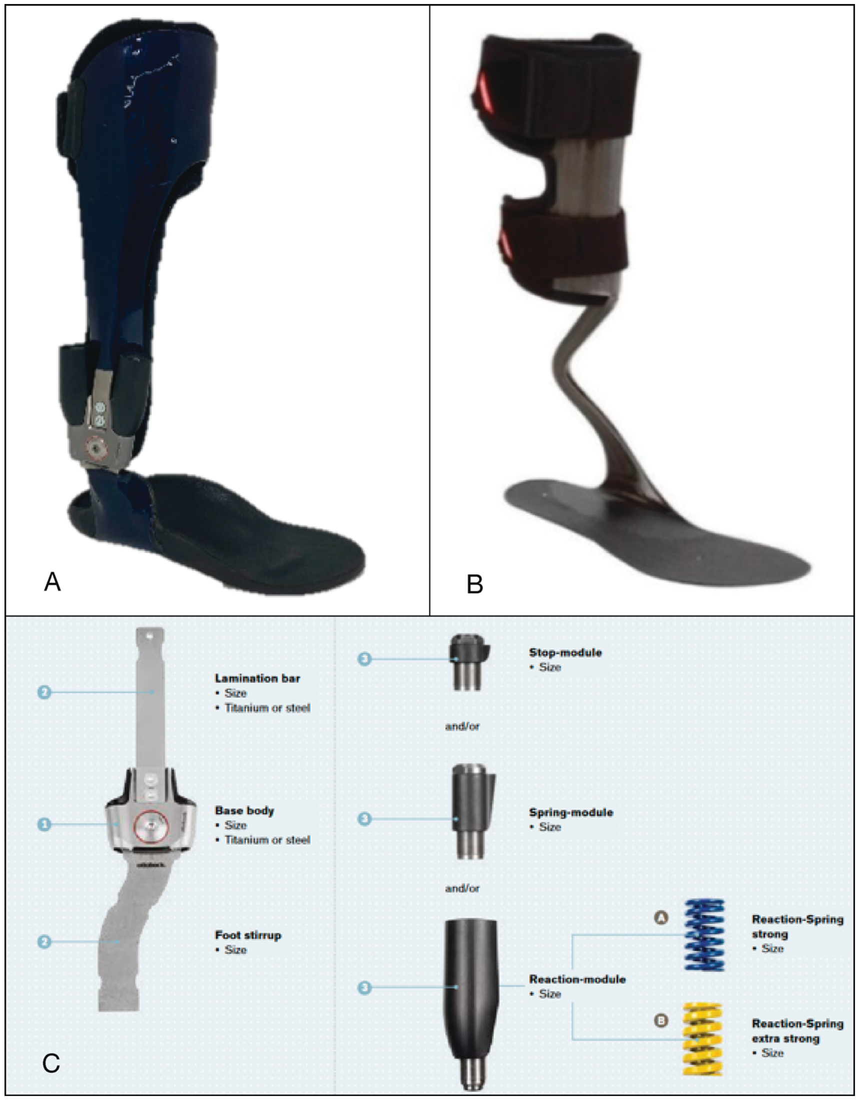

Figure 1. Reactive-dynamic AFO Nexgear Tango (A), Jointless AFO WalkOn Reaction (B), and components of the Nexgear Tango Ankle Joint System, Ottobock SE & Co. KGaA (C).

patients walked with a crouch gait (no full knee extension during stance), two patients with knee joint hyperextension, and three patients with unobtrusive knee joint angle patterns. Other limiting compensatory mechanisms and pathological gait characteristics included increased and unintended ankle dorsiflexion during single-limb stance and decreased ankle power at push-off.

LEVEL WALKING

During level walking, mean gait speed was slightly but nonsignificantly higher with all AFOs compared with without orthosis (WO): v_{RDA} = 1.2 ± 0.3 m/s; v_{JLO} = 1.1 ± 0.2 m/s; v_{CAJ} = 1.1 ± 0.3 m/s; v_{WO} = 1.1 ± 0.3 m/s. Significant benefits of both RDA and JLO over CAJ were shown in mean maximal dorsiflexion angles in stance (DF_{RDA} = 20.1° ± 3.4°; DF_{JLO} = 20.1° ± 2.9°; DF_{CAJ} = 14.4° ± 2.6°; $DF_{W/O}$ = 25.2° ± 3.7°; p_b = 0.02; d = 0.88), and both maximum plantarflexion angle (PF_{RDA} = 16.4° ± 2.5°; PF_{JLO} = 15.6° ± 2.6°; PF_{CAJ} = 8.9° ± 1.2°; PF_{WO} = 21.8° ± 5.3°; p_b = 0.02; d = 0.77–0.88) and ankle joint power at push-off (AP_{RDA} = 1.8 ± 0.8 W/kg; AP_{JLO} = 1.6 ± 0.6 W/kg; AP_{CAJ} = 0.8 ± 0.3 W/kg; AP_{WO} = 1.7 ± 0.9 W/kg; p_b = 0.02; d = 0.86–0.88). Mean values and SDs are presented in Table 3. Pattern analyses showed similar movement patterns for RDA and JLO but deviations for CAJ in the GRF, sagittal ankle joint angle, ankle joint power, and knee joint moment. No other gait parameters showed noticeable differences among the three orthoses, nor between bilateral and unilateral patients, or between left and right side in bilateral patients. Essential kinematic and kinetic parameters are shown for the bilateral patients (left side) in Figure 3.

ASCENDING SLOPES

During uphill walking, RDA enabled a slightly higher gait velocity (v_{RDA} = 0.9 ± 0.4 m/s; v_{CAJ} = 0.8 ± 0.3 m/s; v_{JLO} = 0.8 ± 0.3 m/s; v_{WO} = 0.8 ± 0.3 m/s). However, the differences were not statistically significant, and all values remained substantially lower than the values of the able-bodied control group

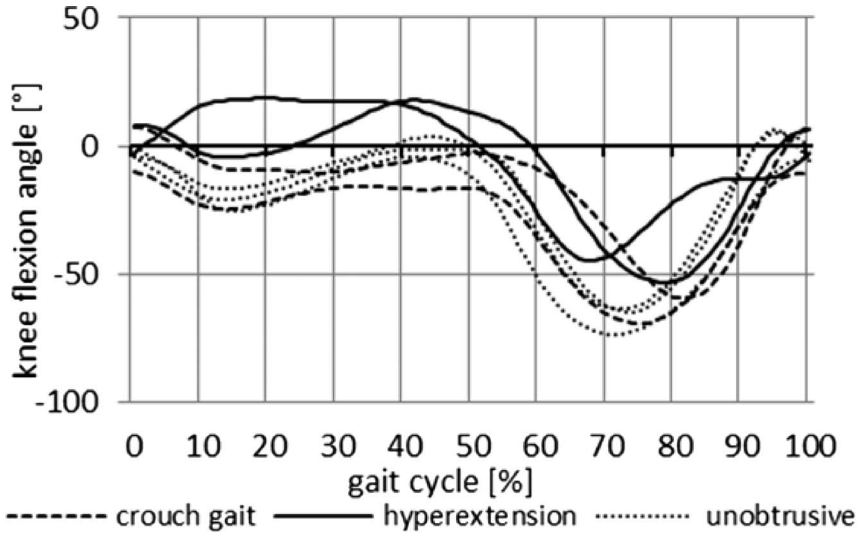

Figure 2. Knee flexion angle in level walking without orthosis.

(v_{CON} = 1.3 m/s). The vertical GRF values were lower with all orthoses compared with the able-bodied controls but did not differ significantly between orthoses. Irregularities in the curve characteristics were observable with CAJ and WO. The ankle joint angle and moment curves showed extreme differences to the normative curve with all orthoses; however, values with RDA and JLO were closest to the normative data. Significant differences between orthoses were observed in the ankle dorsiflexion angle during stance between both RDA and JLO and CAJ (DF_{RDA} = 16.7° ± 2.8°; DF_{CAJ} = 9.1° ± 1.9°; DF_{JLO} = 16.0° ± 3.0°; DF_{WO} 23.6° ± 5.3°; p_b = 0.02; d = 0.89), the final plantarflexion angle between both RDA and JLO and CAJ (PF_{RDA} = 17.9° ± 2.3°; PF_{CAJ} = 9.5° ± 4.1°; PF_{JLO} = 16.4° ± 3.9°; PF_{WO} = 27.1° ± 14.3°; p_b = 0.02; d = 0.89), the maximal ankle joint moment between JLO and CAJ (AM_{RDA} = 1.30 ± 0.23 Nm/kg; AM_{CAJ} = 1.24 ± 0.19 Nm/kg; AM_{JLO} = 1.36 ± 0.20 Nm/kg; AM_{WO} = 0.95 ± 0.40 Nm/kg;

Table 3. Group mean values and standard deviations in level walking with post hoc results

Group mean values + SD	Orthosis configuration			
	RDA	JLO	CAJ	WO
Gait speed (m/s)	1.2	1.1	1.1	1.0
SD	0.3	0.2	0.3	0.3
Max. dorsiflexion angle in stance (°)	$20.1^{c,d}$	$20.1^{c,d}$	$14.4^{a,b,d}$	$25.2^{a,b,c}$
SD	3.3	2.9	2.6	3.7
Final plantarflexion angle at foot-off (°)	$16.4^{c,d}$	$15.6^{c,d}$	$8.8^{a,b,d}$	$21.8^{a,b,c}$
SD	2.5	2.6	1.2	5.3
Max. plantarflexion moment at foot-off (Nm/kg)	1.3^{d}	1.3^{d}	1.3^{d}	$1.1^{a,b,c}$
SD	0.3	0.2	0.2	0.3
Max. ankle power at foot-off (W/kg)	1.8^{c}	1.6^{c}	$0.8^{a,b,d}$	1.7^{c}
SD	0.8	0.2	0.3	0.9
Knee extension range of motion during stance (delta in °)	18.6^{d}	16.4	16.9	15.2^{a}
SD	4.7	5.3	6.9	6.3
Max. knee extension moment during stance (Nm/kg)	0.3	0.3	0.5	0.2
SD	0.3	0.3	0.2	0.3
hip extension range of motion during stance (delta in °)	37.9^{d}	38.8^{d}	38.2	$36.1^{a,b}$
SD	5.2	4.3	4.6	6.0
Max. hip extension moment during stance (Nm/kg)	1.0	1.0	1.0	1.0
SD	0.3	0.3	0.3	0.3

Key: post hoc results.
$^{a}P < 0.05$ to RDA.
$^{b}P < 0.05$ to JLO.
$^{c}P < 0.05$ to CAJ.
$^{d}P < 0.05$ to WO.

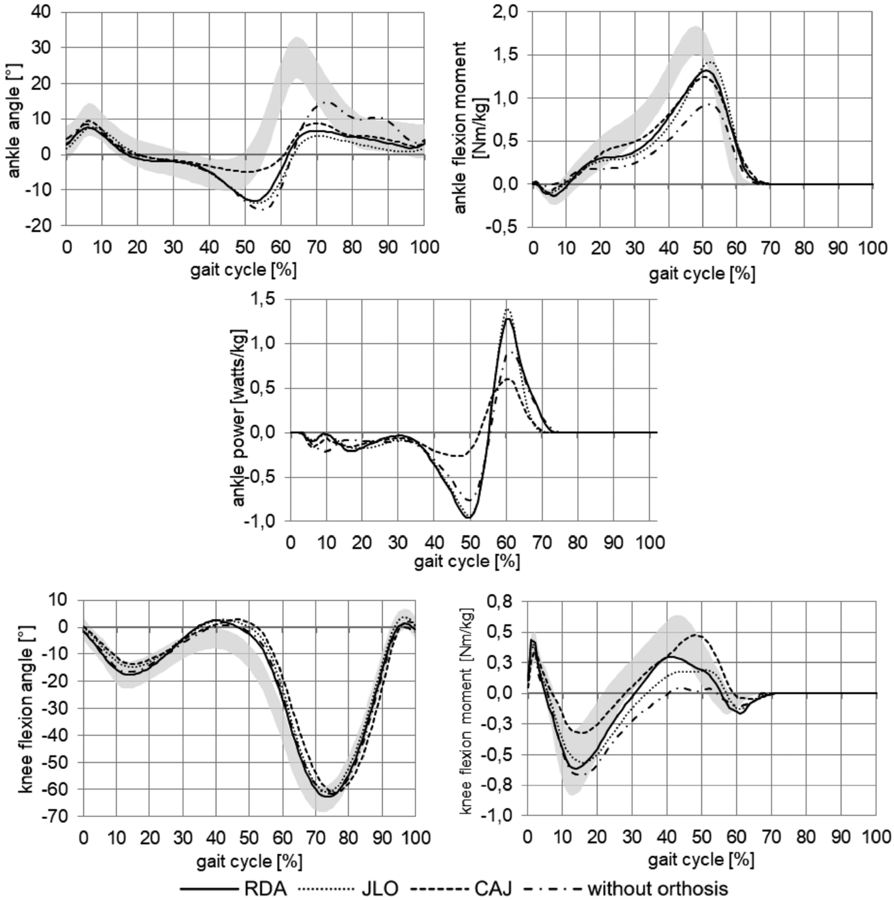

Figure 3. Mean gait parameters during level walking with the reactive-dynamic ankle (RDA), the jointless orthosis (JLO), the conventional ankle joint system (CAJ), and without an orthosis. Data are shown for bilateral patients. The gray data strip represents the normative data of an able-bodied control group where available (mean ± standard deviation).

$p_b = 0.035$; $d = 0.83$), the maximal knee extension moment between RDA and CAJ ($KM_{RDA} = 0.50 \pm 0.11$ Nm; $KM_{CAJ} = 0.70 \pm 0.21$ Nm; $KM_{JLO} = 0.51 \pm 0.23$ Nm; $KM_{WO} = 0.16 \pm 0.25$ Nm; $p_b = 0.045$; $d = 0.80$), as well as the maximum ankle joint power at push-off between both RDA and JLO and CAJ ($AP_{RDA} = 1.29 \pm 0.74$ W/kg; $AP_{CAJ} = 0.65 \pm 0.23$ W/kg; $AP_{JLO} = 1.50 \pm 1.10$ W/kg; $AP_{WO} = 1.17 \pm 0.91$ W/kg; CAJ vs. NXT $p_b = 0.027$; $d = 0.86$; CAJ vs. WOR $p_b = 0.02$; $d = 0.89$). These values confirmed the observed differences in the descriptive pattern analyses, which showed a decreased ankle ROM and a conspicuous early peak in the ankle joint moment with CAJ compared with the curve from the able-bodied controls, and similar values compared with the able-bodied controls with RDA and JLO for ankle joint moment and power.

Without orthosis, patients demonstrated no or very low extension moments in the knee and ankle joint. With RDA and JLO, higher extension moments were measured. CAJ seemed to enable similar absolute moment values to RDA and JLO; however, the values rose abruptly and inconsistently (see Figure 4). No significant differences were observed between the orthoses at the hip joint during uphill walking. During stance in uphill walking, all participants showed a slight hyperextension in the knee joint. This effect was not observed WO.

DESCENDING SLOPES

During downhill walking, gait velocity differed only slightly and inconclusively between orthosis situations and participants. The ankle flexion angle showed a reduced dorsiflexion during stance with RDA, JLO, and without, compared with CAJ; however, this difference was only statistically significant between each orthosis and the situation without ($DF_{RDA} = 26.9° \pm 5.9°$; $DF_{CAJ} = 18.3° \pm 4.1°$; $DF_{JLO} = 24.5° \pm 4.7°$; DF_{WO} $35.9° \pm 4.5°$; $p_b = 0.046$; $d = 0.80$, see Figure 5). Final and maximal plantarflexion at push-off differed significantly between CAJ and all other orthoses ($PF_{RDA} = 18.0° \pm 4.2°$; $PF_{CAJ} = 9.3° \pm 2.5°$; $PF_{JLO} = 17.1° \pm 2.7°$; $PF_{WO} = 28.2° \pm 10.8°$; $p_b < 0.05$; $d = 0.80–0.89$) but not between RDA and JLO or between RDA and WO. No significant differences were found for the knee joint kinematics and kinetics in this motion task. Hip flexion and extension angle showed significant differences between CAJ and all other orthoses ($HA_{RDA} = 19.3° \pm 3.9°$; $HA_{CAJ} = 16.2° \pm 3.0°$; $HA_{JLO} = 19.1° \pm 3.7°$; $HA_{WO} = 21.3° \pm 4.2°$; $p_b < 0.05$; $d = 0.80–0.86$). Descriptive pattern analysis confirmed these results and, furthermore, showed the largest irregularities with CAJ compared with the other two orthoses in most parameters (Figure 5).

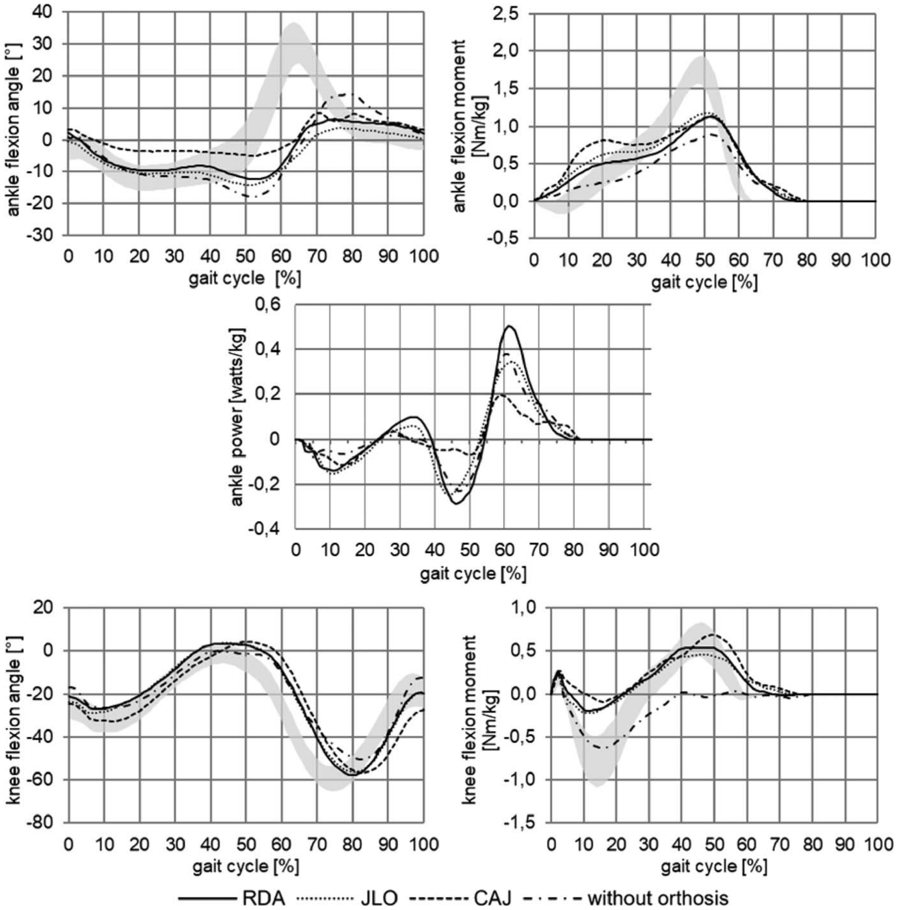

Figure 4. Mean gait parameters when ascending ramps with the reactive-dynamic ankle (RDA), the jointless orthosis (JLO), the conventional ankle joint system (CAJ), and without an orthosis. Data are shown for bilateral patients. The gray data strip represents the normative data of an able-bodied control group where available (mean ± standard deviation).

STANDING

When standing without assistance on level ground, mean ankle flexion angles differed significantly between RDA and CAJ versus JLO and without (AA_{RDA} = 115.9° ± 3.8°; AA_{CAJ} = 116.9° ± 3.8°; AA_{JLO} = 109.8° ± 3.4°; AA_{WO} = 108.7° ± 3.6°; p_b = 0.02; *d* = 0.86–0.88). For reference, previous measurements with an able-bodied control group reported a mean ankle flexion angle of 111° (Höncher, 2012). Knee flexion angles of the patient group did not show significant differences, whereas the hip flexion angle differed significantly between RDA and WO (HA_{RDA} = 93.5° ± 3.1°; HA_{CAJ} = 93.7° ± 3.1°; HA_{JLO} = 92.3° ± 3.4°; HA_{WO} = 91.6° ± 3.5°; p_b = 0.03; *d* = 0.86). Differences between the other orthoses were no longer significant after Bonferroni correction. The mean hip flexion angle of an able-bodied control group was found at 92°.[25] When standing uphill, similar effects were observed: ankle flexion angles differed significantly between each RDA and CAJ and without, as well as between each RDA and CAJ and JLO (AA_{RDA} = 108.5° ± 3.9°; AA_{CAJ} = 112.3° ± 6.1°; AA_{JLO} = 103.3° ± 3.2°; AA_{WO} = 98.6° ± 3.4°; $p_b < 0.05$; *d* = 0.80–0.83). For reference, in the previous measurements in an able-bodied control group, standing uphill on the same slope resulted in a mean ankle flexion angle of 101°.[25] The knee and hip flexion angles showed no significant differences between the orthoses. When standing downhill, only the ankle flexion angle differed significantly between CAJ and JLO (p_b = 0.02; *d* = 0.88) and JLO and RDA (p_b = 0.03; *d* = 0.86) (AA_{RDA} = 122.7° ± 3.6°; AA_{CAJ} = 125.1° ± 5.1°; AA_{JLO} = 114.7° ± 6.1°; AA_{WO} = 118.6° ± 3.5°). The mean ankle flexion angle of the able-bodied control group when standing downhill was 122°.[25] Although the knee flexion angle did not display meaningful descriptive or statistically significant differences between the orthoses, it was slightly higher in all standing situations compared with the able-bodied control group.[25] Weight distribution between right and left leg was also measured. However, these results showed no statistical significance (1%–20%). Only one participant showed a meaningful difference between right and left, in the situation without.

PARTICIPANTS' PERCEPTION

The RDA was rated as 8.6/10 (uphill) and 8.8/10 (downhill) for standing on slopes and 9.0–9.4/10 for walking tasks. JLO was rated 4.1/10 (uphill) and 5.2/10 (downhill) for standing on slopes and 4.5–5.0 for walking tasks. CAJ was rated 3.6/10 (uphill) and 5.2/10 (downhill) for standing on slopes, and 4.5–5.5 for walking tasks. The difference between the orthoses was stated to be particularly impactful during uphill walking by 71% of the participants, followed by downhill walking and

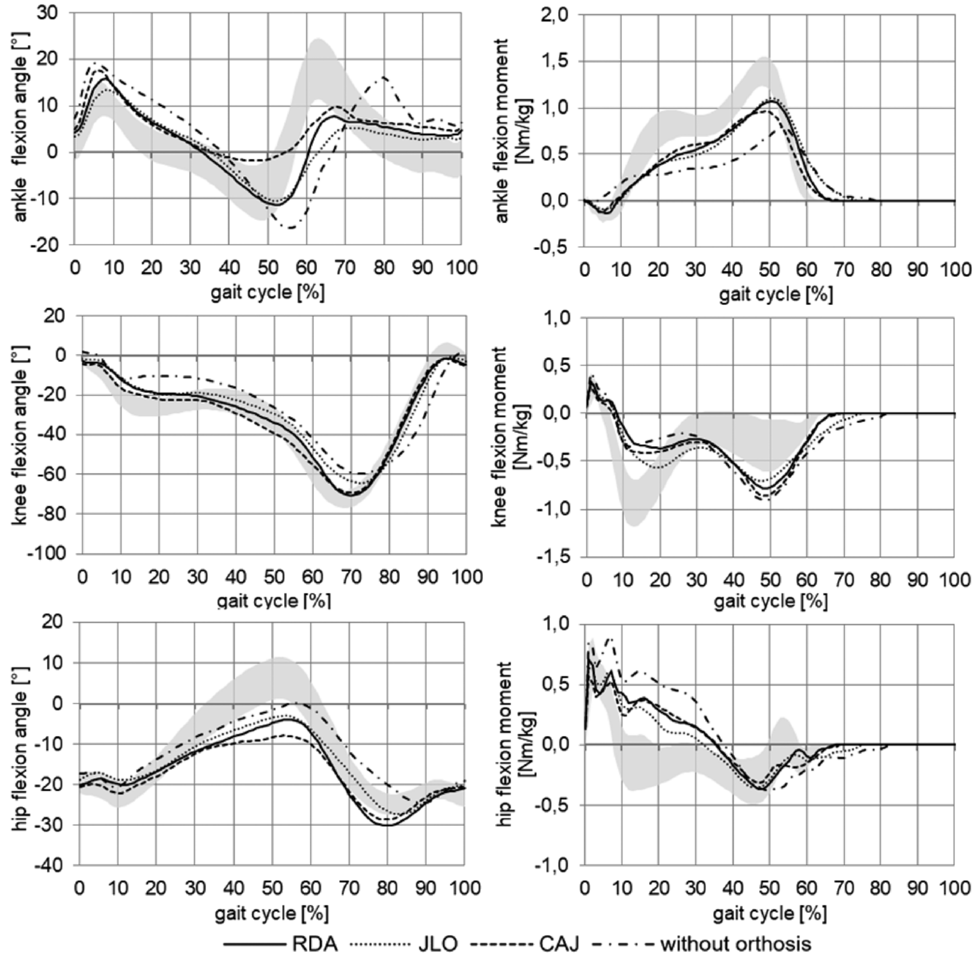

Figure 5. Mean gait parameters when descending ramps with the reactive-dynamic ankle (RDA), the jointless orthosis (JLO), the conventional ankle joint system (CAJ), and without an orthosis. Data are shown for bilaterally affected patients. The gray data strip represents the normative data of an able-bodied control group (mean ± standard deviation).

standing on slopes (57% each), compared with the other motion tasks. Fourteen percent of participants noted the orthoses type to be particularly relevant during level walking. Major benefits of the RDA were stated in the aspects of support, perception of safety, and maintaining stability for more enduring or demanding ADLs.

DISCUSSION

The innovative approach within this study was the analysis of differential benefits between a new generation of AFOs (RDA) and two established AFO principles, a JLO and a CAJ. The RDA was expected to have advantages over JLO and CAJ in the tested motion tasks, due to the reactive coil spring modules, which enable adjustable damping, accelerating, and energy return.

In comparison to the CAJ, RDA showed clear benefits in all the tested motion tasks. The kinematic data showed a larger ROM and higher peak joint moment of the ankle, which in turn enabled a joint angle and moment pattern closer to that of able-bodied controls. Major restrictions of the CAJ were clearly visible when observing the reduced dorsiflexion angle and the rugged rollover in the ankle during stance. These observations are in line with reports from previous studies.[21] When wearing the RDA, participants showed reduced compensatory crouch or hyperextension movements in the knee joint compared with when wearing the CAJ. Furthermore, CAJ seemed to evoke partially abnormal knee loading as well as irregular knee extension across different phases of the gait cycle, which participants did not show when wearing the RDA. RDA also seems to allow for more energy to be stored during rollover and released during push-off, compensating for functions of the weakened shank muscles. Therefore, the ankle power showed a smoother curve during the gait cycle and significantly higher peak power output at push-off with RDA than with CAJ.[21] This effect was particularly large during uphill walking. Previous studies investigating conventional, non–energy-storing-and-returning orthoses in patient groups with similar gait pathologies reported similar results.[17,26,27] During downhill walking, the damping effect of the RDA enabled an ankle dorsiflexion and plantar flexion closer to norm values from the able-bodied control group and seemed to reduce compensatory movement in the hip joint compared with CAJ. In bipedal stance, CAJ and RDA showed no conspicuous differences in ankle, knee, or hip flexion angles. The results of the participants' subjective perception confirmed the biomechanical analysis and showed a clear preference for the RDA over the CAJ. All patients commented on this preference verbally or in written form, explicitly explaining that they had also perceived reduced effort when walking longer distances with the RDA, as well as a safer and more comfortable gait.

In comparison to the JLO, the superiority of RDA was less clear. The flexible properties of the JLO seemed to support a larger ROM of the ankle joint than the CAJ and showed values close to those reached with RDA in all walking tasks. Joint moments of the knee and ankle also resembled those reached with RDA. These results are in line with several previous investigations, which reported a significant benefit of carbon fiber ground reaction JLOs while walking on level ground and uphill, resulting in gait velocities and kinematics similar to data of able-bodied controls.[26,28–30] The analysis of ankle joint power, however, showed higher values when using the RDA for walking up the 10° incline compared with the JLO, suggesting a superior energy storage and return capability of the RDA. During bipedal stance, only small changes were evoked with both RDA and JLO, whereby JLO showed hip, knee, and ankle angles slightly but insignificantly closer to able-bodied norms than RDA during uphill and level stance.[25] Both orthoses showed almost equal joint angles in downhill stance. The evaluation of participants' perception confirmed the similar biomechanical effects of JLO and RDA during level walking, particularly in those patients with less muscular impairments and physically fit. This was confirmed in studies with children reporting positive correlations of preference for the stronger spring AFO with increasing growth and motor skill acquisition.[31] However, all patients also reported perceiving reduced stability and safety with JLO compared with RDA. From previous experience, the more active participants also reported JLO to insufficiently support longer walking distances and walking on uneven terrain. These statements confirm reports from a previous single case study on a similar orthoses comparison.[21]

LMITATIONS AND FUTURE OUTLOOK

The motion tasks tested within this study were limited to a laboratory setting with relatively short walking distances and slopes up to 10° inclines, up to which JLO and RDA seem to enable similar kinematics. However, considering subjective perception ratings and verbal comments from patients, difficulties with JLO are to be expected on steeper inclines, as well as over longer walking distances on level and inclined ground. Under such circumstances, an efficient energy return and a smooth, natural rollover without rigid stops may become more relevant. To show these factors in quantitative study data in the future, biomechanical and physiological comparisons should be made over longer testing periods in everyday life and during more coordinatively demanding or physically exhausting tests. Additionally, future studies should incorporate tests to adequately quantify metabolic energy consumption, as this aspect was also repeatedly mentioned as an advantage of RDA compared with both CAJ and JLO during participants' perception reporting. The small and insignificant differences in kinematics during stance contradict individual comments from participants on the effort needed with the different orthosis models. This indicates that strategies to maintain balance in stance may not be compensated by varying joint angle relations but perhaps rather by varying muscle activity to maintain the required joint angle relations. Future studies should, therefore, incorporate electromyography measurements to study muscle activity during stance.

CONCLUSIONS

Overall, the results of this study showed significantly superior results in almost all gait parameters with RDA compared with CAJ. From a biomechanical perspective, JLO and RDA seemed to show similar benefits in the motion tasks tested within this study, suggesting a JLO may be sufficient for patients with such or similar activities in their day-to-day life and a comparable level of muscle weakness. However, subjective perception analysis implied that RDA may be favorable for more demanding and strenuous activities, such as ascending or descending longer and steeper inclines, walking long distances or across uneven surfaces. RDAs may therefore be primarily suitable for highly active patients with high expectations toward their orthotic care.

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