Orthotics

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The Biomechanical Benefit of a Freely Moving System Knee Joint with a Dynamic Extension Stop

Knee-ankle-foot orthoses (KAFOs) with freely moving system knee joints are often prescribed for patients with neurological gait disorders to achieve security and stability when walking and standing. In these types of orthotic joints, extension stops are used to prevent the pathological hyperextension of the knee. A dynamic extension stop enables controlled extension of the knee through the adjustable resistance of the anterior spring unit without restricting the patient's range of motion. The article first describes the biomechanical benefit of this innovative functional element and then presents the results of a case study that determined that a KAFO with a dynamic extension stop improves joint kinematics compared to a KAFO with a static extension stop.

Key words: system knee joint, dynamic extension stop, orthosis, biomechanics

Introduction

System knee joints are divided into groups according to their functions and consist of the following types: freely moving system knee joints, automatic system knee joints (stance phase stability joints) and locked system knee joints. Freely moving system knee joints are primarily used in the fabrication of custom KAFOs. They can also be designed with or without integrated posterior placement. The operating principles behind these two joint functions vary in only a few aspects which, however, are highly relevant to the patient and for this reason are discussed in greater detail below.

Purpose of freely moving system knee joints without posterior placement

Freely moving system knee joints without posterior placement permit uninhibited movement in both the stance and swing phases. They provide lateral stability and guidance for the anatomical knee joint during the motion sequence. The mechanical knee axis is positioned congruently to the anatomical compromise pivot axis according to Nietert [1] (Fig. 1a). Displacement between the leg and orthosis is thereby reduced to a minimum; the device is comfortable to wear and prevents strain during use. This type of system joint is recommended for patients who have adequate muscle strength to counter the knee flexion moment during loading response. The knee is stabilised entirely by the muscles.

Purpose of freely moving system knee joints with posterior placement

Functional deviations due to minor muscular limitations of the knee extensor muscle groups can be compensated for by means of posterior placement of the mechanical knee joint axis in a freely moving system knee joint. This mechanical knee axis is not positioned congruently to the anatomical compromise pivot axis but rather behind it (Fig. 1b). The knee is passively stabilised as a result of the incongruence of the joint axes [2]. In order to counter the flexion moment during loading response, the orthosis supports the muscles that are not fully functional due to the posterior placement of the mechanical centre of rotation of the knee joint. The knee is stabilised by a combination of muscle strength and joint function; the posterior placement of the centre of rotation resulting from the joint's design ensures that the system anchors and bars can nonetheless be centrally aligned on the upper and lower leg.

Extension stops in freely moving system knee joints

The following section starts by providing a detailed explanation of the biomechanical function of an extension stop in a KAFO. Two types of extension stops are then presented.

Function of the extension stop

The extension stop (ES) defines the maximum extension of the knee. In a healthy human knee, flexion and extension are controlled by the muscles. If the muscles that stabilise the knee are impaired, this can result in excessive strain on the anatomical ligament system in the knee. For this reason, orthotic devices spanning the knee should incorporate a functional element that limits knee extension in order to prevent pathological hyperextension of the knee [3]. When walking with a KAFO, the ES is reached in the gait phases in which the ground reaction force vector passes in front of the mechanical centre of rotation of the system knee joint. In the stance phase, this occurs during initial contact, mid-stance and terminal stance.

In addition to preventing pathological hyperextension in the stance phase, the ES also limits the forward swing of the lower leg at the end of the swing phase in terminal swing.

Types of extension stops

Freely moving system knee joints are available with various types of ES. Modular system knee joints allow the joint function to be individually adapted to the needs of the patient. The knee joint can be limited in the extension direction by means of various types of stops. These are divided into two functional groups: static and dynamic extension stops. These two variants are described in more detail below.

Static extension stop

The static ES limits the maximum knee extension to a specified rigid angle. For this reason, extension movement is not possible beyond this specified stop position, thus limiting the range of motion of the knee in the extension direction. The ES can be replaced in many orthotic joints so the knee angle of the orthosis can be adjusted. The interchangeable ESs are available in increments of 5° or 10°. System knee joints with continuously adjustable ESs can be set with far greater precision, allowing the knee angle to be set within a range of 0° knee extension to 20° knee flexion.

Dynamic extension stop

The dynamic ES limits knee extension against the spring-loaded resistance of an anterior spring unit. The extension movement this permits extends beyond the continuously adjustable knee angle of the orthotic joint (e.g. from 5° knee flexion towards 0° knee extension). The spring stiffness and maximum range of motion can be individually adjusted via interchangeable spring units. The range of motion of the spring path can also be continuously limited by means of a movement limiting screw without the patient having to remove the orthosis for this purpose.

Dynamic extension stop in a KAFO

The primary objective of an orthotic device is to restore physiological standing and walking – however, in any case, the device should improve the gait pattern. In order to achieve this goal as effectively as possible, a modern KAFO should limit the range of motion of the affected joints to the least possible extent [4]. The additional freedom of movement provided by the dynamic ES fulfils this requirement. In the following section, we describe the adjustability and biomechanical benefit of the dynamic ES in greater detail.

Adjustability of the joint angle

The O&P technician fitting the device determines the knee angle at which the ES is to be reached based on the bench alignment of the orthosis. An alignment with 5° knee flexion and 5° forward tilt of the tibia has proven effective in practice [5]. This slight knee flexion is geared towards the physiological joint angles during walking and results in a significantly more dynamic gait in comparison to a straight alignment of the orthosis. The ES thus describes the knee angle and the forward tilt of the tibia at the transition from the mid-stance to terminal stance phase. The continuous adjustability of the system knee joint presented in this article with a dynamic ES (extension stop) serves as an ideal complement to a system ankle joint with a continuously adjustable dynamic dorsal stop. This makes it possible to adjust or counter-adjust the knee flexion according to the forward tilt of the tibia that has been set (Fig. 2).

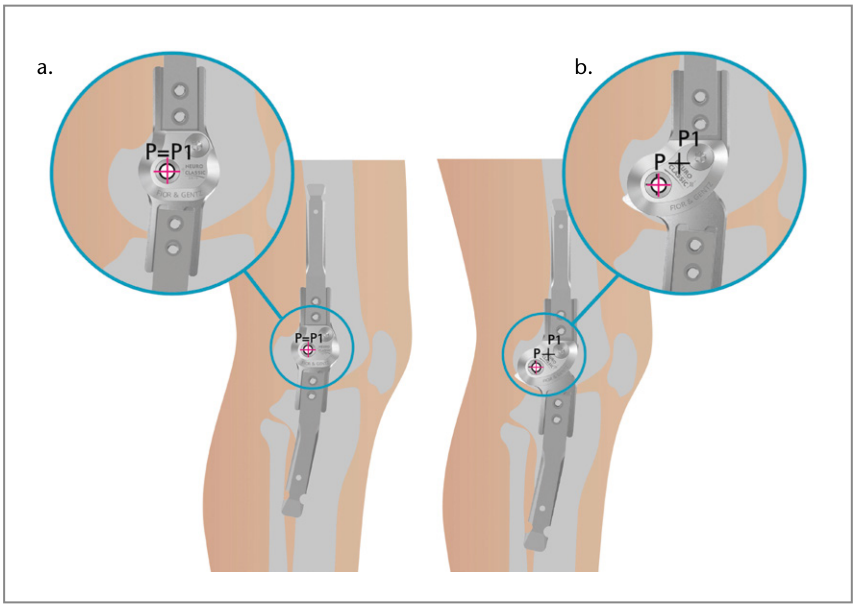

Fig. 1a & b Freely moving system knee joint; a) without posterior placement: the position of the mechanical knee axis (P) is congruent to the anatomical compromise pivot axis (P1) according to Nietert; b) with posterior placement: the mechanical knee axis (P) is positioned behind the anatomical compromise pivot axis (P1) according to Nietert.

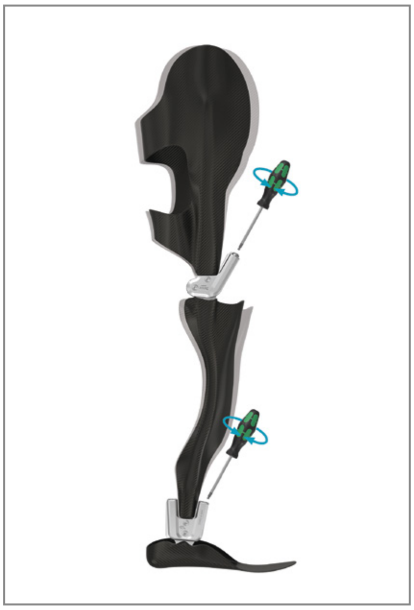

Fig. 2 The bench alignment of the orthosis is set by continuous adjustment of the knee and ankle joint.

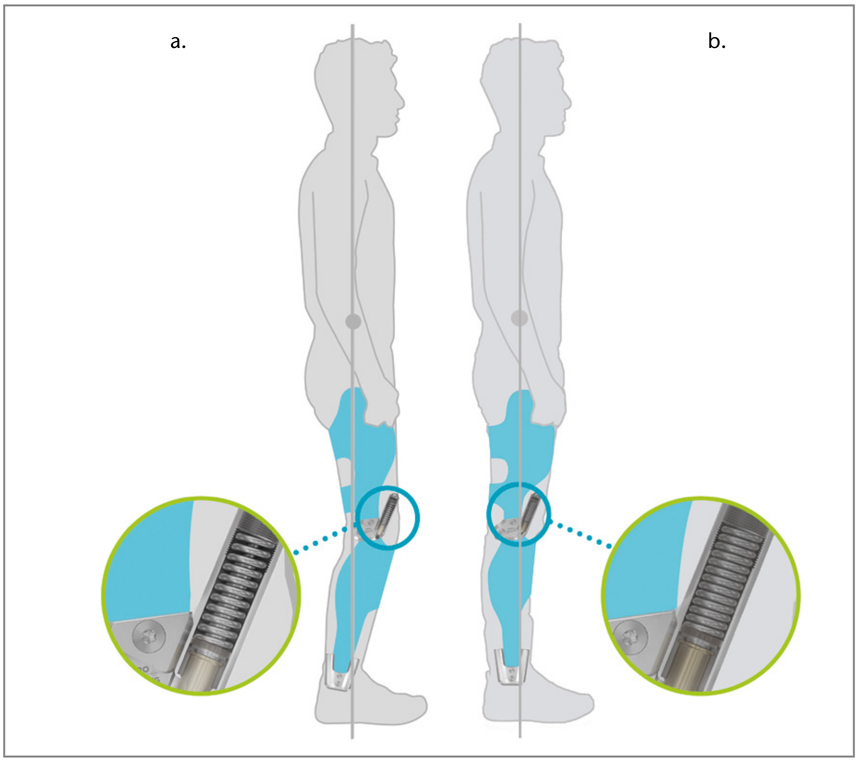

Fig. 3a & b Biomechanical benefit of the dynamic ES during standing; a) bench alignment with the knee slightly flexed; b) knee stabilised by means of physiological hyperextension against the resistance of the anterior spring unit.

Biomechanical benefit

By permitting greater freedom of movement in the direction of knee extension compared to the static ES, the dynamic ES provides the patient with controlled, physiological freedom of movement when the knee angle is properly set and an adequate spring stiffness is selected – during both standing and walking. The following sections address this in detail.

Standing

The right balance ensures the patient's safety during standing. Passive stability is anatomically generated when standing due to the slight hyperextension of the knee and hip joint. This physiological hyperextension results in the knee being stabilised, as the ground reaction force vector runs behind the hip and in front of the knee joint axis in this position. The opposing forces in the form of the ligamentous tension of the posterior cruciate ligament and the iliofemoral ligament stabilise the knee in posterior and the hip joint in anterior direction [6]. This anatomical knee stabilising effect is enhanced by the posterior placement of the mechanical knee axis of the system knee joint. Based on the knee flexion taken into account in the bench alignment of the orthosis (Fig. 3a), the knee can extend further against the resistance from the anterior spring unit (Fig. 3b), which has a positive influence on the patient's safety during standing and comfort while wearing the orthosis. In other words, patients fitted with the orthosis already benefit from the function of the dynamic ES while standing.

However, the described knee stabilising function is possible only if the dynamic system knee joint is combined with a dynamic system ankle joint that permits freedom of movement in plantar flexion. Plantar flexion movement is required in the upper ankle joint so the knee can extend further from the slightly flexed position. This is made possible by the heel rocker function of the system ankle joint.

Walking

The dynamic ES limits knee extension based on the model of the physiological gait pattern. The physiological course of the knee angle during walking (Fig. 4) illustrates the biomechanical benefit of the dynamic ES, which enables full extension of the knee. Full extension of the knee is physiological for many patients in the stance phase, or to be more precise during terminal stance (TSt) [7]. The knee joint can even hyperextend slightly here. In addition, knee extension that varies individually and amounts to up to 3° hyperextension occurs shortly before the end of the swing phase

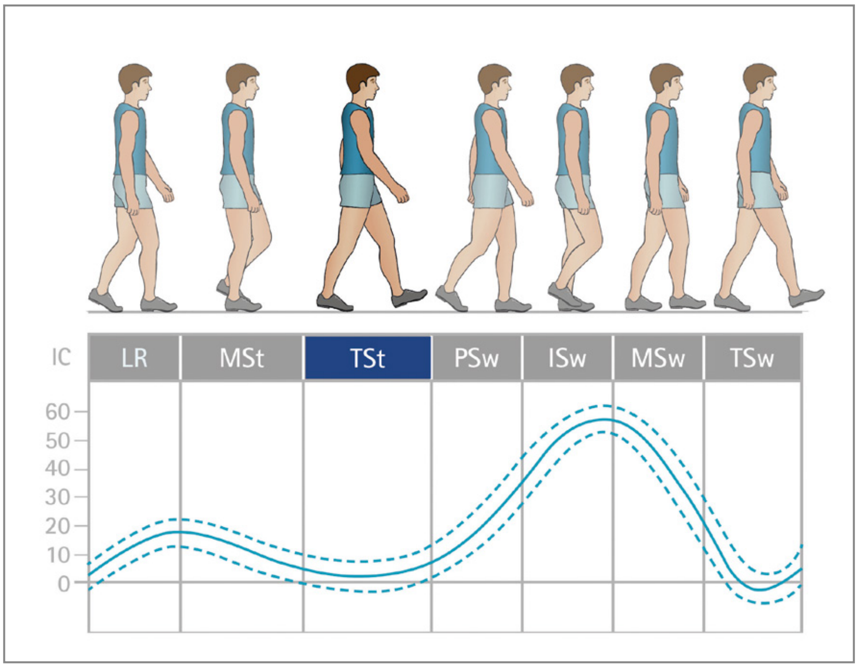

Fig. 4 Physiological course of the angle in the knee joint, modified according to [6].

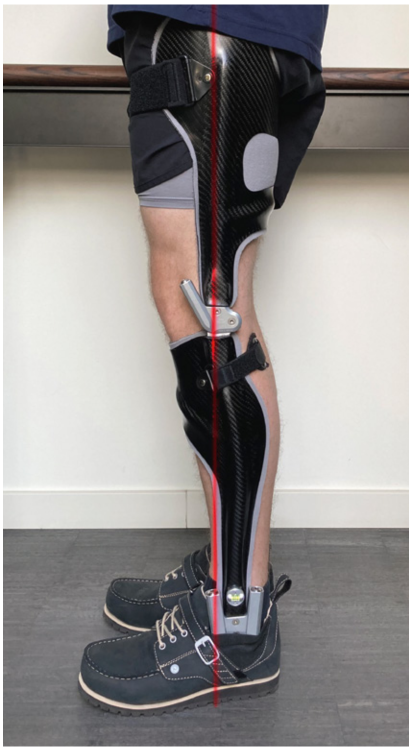

Fig. 5 Static alignment of the test orthosis on the test subject.

in terminal swing (TSw). During subsequent initial contact (IC), the knee is extended or also slightly hyperextended [7]. A closer look at the kinematics of the knee makes it clear that walking with physiological joint angles can be attained only when freedom of movement is restricted to the least possible extent by the functional elements of the orthosis. These circumstances highlight the biomechanical benefit the dynamic ES offers as a result of the freedom of movement afforded by the anterior spring unit. In addition to the biomechanical benefit, the soft, cushioned stop of the anterior spring unit has a positive influence on the comfort of the orthosis during wear.

Case study

A case study was conducted in order to quantify the described biomechanical benefit that a dynamic ES provides in a KAFO. During this process, measuring technology was used to determine the hip, knee and ankle kinematics of a healthy subject in the sagittal plane during standing and walking with a KAFO. The aim was to analyse whether a dynamic ES permits greater freedom of movement in the knee extension direction than a static ES, thus influencing standing and walking.

Methods

The analysis was carried out on a healthy 31-year-old male test subject (180 cm, 80 kg). The test orthosis was a customised KAFO for the left leg that was fabricated using fibre composite technology and consisted of a system ankle joint with a dynamic dorsal and plantar stop as well as a freely moving system knee joint with posterior placement and dynamic ES. The movement limiting screw of the joint allowed the anterior spring effect to be blocked to the maximum extent, generating a functionally static ES. This enabled a comparison between the static and dynamic ES using the same orthosis.

The bench alignment of the orthosis was carried out – as described in the 'Adjustability of the joint angle' section – with the knee slightly flexed at approx. 5° as well as with a physiological forward tilt of the tibia of likewise approx 5° (Fig. 5). The selection of the spring stiffnesses of the dynamic knee and ankle joints was calculated using an orthosis configurator [8] taking into account the specific data of the subject. The selected posterior and anterior spring unit of the system ankle joint permits maximum freedom of movement of 10°, while that of the anterior spring unit of the system knee joint is 9°. A stance and gait analysis was conducted with the static and dynamic ES respectively by means of a video-based 2D gait analysis system. Software was used to measure the angles by tracking anatomical reference points that had reflective markers.

For both types of stops, three images were first taken in the standing position followed directly thereafter by images of three complete double paces, and the courses of the hip, knee and ankle angles were determined on this basis. The orthosis was not removed during the change in function after the images with the static ES in order to keep measuring errors to a minimum. The movement limiting screw of the system knee joint was unscrewed to make the full range of motion of the anterior spring unit available to the test subject for the recording with the dynamic ES.

	Static ES		Dynamic ES		
Hip	-5,8°	±0,1	-8,7°	±1,0	*
Knee	8,3°	±0,7	4,0°	±1,0	*
Ankle	3,9°	±0,6	2,3°	±1,5	

***Tab. 1** Joint angles determined during standing with static and dynamic ES (* = significant differences between the two conditions)*

		Static ES		Dynamic ES		
ROM	Hip	39,8°	±0,7	42,2°	±0,6	*
	Knee	66,8°	±0,5	69,6°	±0,9	*
	Ankle	13,1°	±0,6	13,0°	±0,6	
Hip extension	Pre Swing	-19,0°	±0,5	-22,0°	±0,5	*
Knee extension	Initial Contact	6,4°	±0,3	3,5°	±1,0	*
	Terminal Stance	8,0°	±0,2	4,8°	±0,6	*
	Terminal Swing	4,1°	±0,4	0,8°	±0,2	*
Plantar flexion	Loading Response	-5,3°	±0,4	-5,4°	±0,7	
	Initial Swing	-2,0°	±1,1	-3,6°	±0,5	*

***Tab. 2** Range of motion (ROM) and maximum joint extension of the hip, knee and ankle with static and dynamic ES (* = significant differences between the two conditions according to the Wilcoxon rank sum test, $\alpha = 0.20$).*

In order to analyse the measurements in the standing position, the mean and the standard deviation were calculated respectively based on all three measurements from the hip, knee and ankle angle for both types of stops. During walking, the double pace was analysed for significant variations between the static and dynamic ES with respect to the following aspects:

1. complete range of motion (ROM) of hip, knee and ankle
2. maximum hip extension (in pre-swing), maximum knee extension (in initial contact, terminal stance and terminal swing) and maximum plantar flexion (in loading response and initial swing).

The Wilcoxon rank sum test ($\alpha = 0.20$) was used to check the statistical variations.

Results

Standing

Significant increases in the hip extension (3°) and knee extension (4°) were identified with the dynamic ES in comparison to the static ES. However, the accompanying increase in plantar flexion of 2° does not have any statistical significance (Tab. 1).

Walking

The ROM of the sagittal hip (2°) and knee angle (3°) is increased when using the dynamic ES compared to the static ES. In addition, hip extension in pre-swing and knee extension in initial contact, terminal stance and terminal swing are significantly increased by 3° respectively. The plantar flexion of the ankle joint in initial swing with the dynamic ES is also increased by 2° compared to the static ES (Tab. 2, Fig. 6).

Discussion

The described biomechanical benefit of a system knee joint with dynamic ES was quantified using measuring technology during both standing and walking. In both situations, more physiological knee extension was achieved as a result of the additional freedom of movement provided by the anterior spring unit of the system knee joint compared to the use of the static ES. Increased knee extension in initial contact, terminal stance and terminal swing creates the basis for greater freedom of movement of the knee joint. The measuring results clearly show that improved knee extension in terminal stance is also followed by an increase in hip extension in pre-swing as well as in push-off in initial swing. The connection between these changes and the knee kinematics is rather indirect; however, it is possible that the increase in knee extension had an effect on the other joints due to an elongation of the plantar flexor muscle chain. Taken together, these changes result in a measurable improvement in the gait pattern.

In terms of the measuring results, however, it is important to consider that the gait analysis was carried out with a healthy test subject – so muscular compensations on the part of the subject may have influenced the results. A case series of patients with neurological gait disorders would have the potential to demonstrate the biomechanical benefit that a system knee joint with dynamic ES has on the pathological gait pattern. Additional measurements of spatial and temporal parameters could provide information on whether the added freedom of movement influences the stride length and speed.

Conclusion

The use of a system knee joint with dynamic ES in a KAFO can further enhance the quality of orthopaedic treatment provided to patients with neurological gait disorders. Standing and walking with physiological joint angles can be optimised as a result of the biomechanical benefit this functional element provides in a KAFO. Patients benefit from increased freedom of movement at the

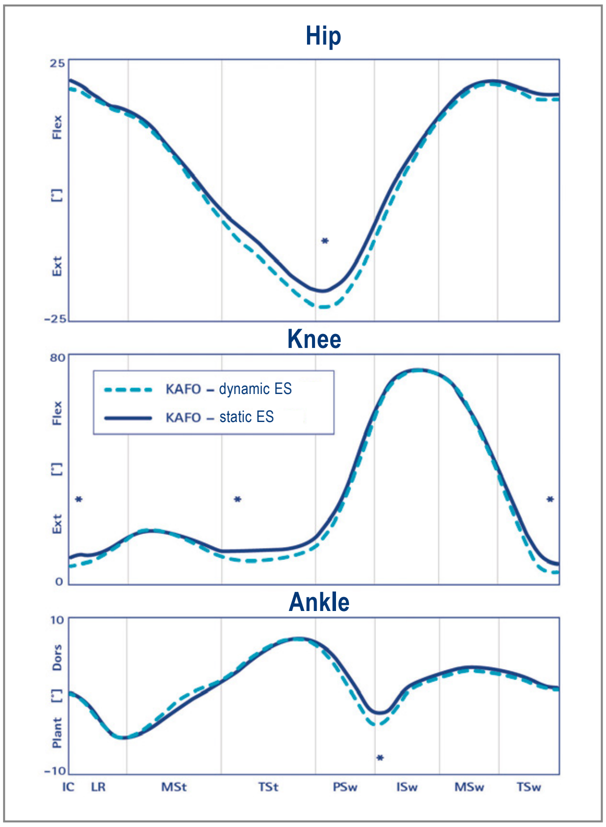

Fig. 6 *Joint kinematics of the hip, knee and ankle in the sagittal plan when walking with a freely moving system knee joint; dynamic ES (dotted line) vs. static ES (solid line) (* = significant differences between the two conditions (Wilcoxon rank sum test, α = 0.20).*

knee level and the work of the orthopaedic technician is facilitated by the comprehensive adjustment options and modular nature of the system knee joint. The orthosis can be adjusted precisely to the safety requirements of the patient. The highly functional dynamic ES thus represents a useful expansion of the selection of system knee joints available on the market.

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