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Second generation prototype of a variable stiffness transverse plane adapter for a lower limb prosthesis

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ABSTRACT

The prescription and fitting of a traditional lower limb prosthesis often focuses on straight walking, neglecting maneuvers such as turning and pivoting that require flexibility in the transverse plane. Current devices that allow transverse plane movement only offer a fixed stiffness and are incapable of adapting to varying daily activities. Pilot testing of a first-generation variable stiffness torsion adapter (VSTA I) showed a benefit for individuals with lower limb amputation by reducing peak transverse plane moments at the residual limb which could lead to increased comfort, but testing was limited due to excessive device height and mass. The VSTA II, a second-generation prototype, is capable of discrete stiffness variation from 0.31 to 1.29 Nm/° in 0.25 Nm/° increments with ±30° of motion in addition to fully locked operation. Stiffness variation is enabled by five independent spring subunits that can be combined in parallel to create different, linear, stiffness settings. The VSTA II features a reduced mass (51% reduction) and height (42% reduction) compared to its predecessor along with a tether-free controller and power system. These improvements will permit greater recruitment for amputee studies, and allow for advanced testing both in and out of the lab.

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1. Introduction

The role of a prosthesis is to restore the abilities of the original intact limb and return the individual back to the highest activity level possible. Prosthesis innovations often focus on straight walking tasks, with little attention paid to activities such as turning and twisting that require transverse plane motion [1–3]. Turning steps that include transverse plane motion comprise a significant portion of daily steps [4]. The inclusion of a transverse rotation adapter (TRA) has been associated with increases in amputee stability and activity level, as well as improved ability to negotiate turns [5–7]. Commercially available TRAs only allow for single stiffness settings set by a prosthetist and cannot adjust to the varying activities of daily life [8,9].

A variable stiffness torsion adapter (VSTA I) was previously designed and tested [10,11]. It was found that reduced transverse plane stiffness in the shank of a lower limb prosthesis could significantly reduce peak loading on the residual limb with no effect to user mobility. Reduction in limb loading can translate to reduced soft tissue damage and increased user comfort [12]. While initial results using the VSTA I were promising, it has not yet been determined what level of transverse plane stiffness would be optimal for varying walking speeds and activities. Because of this, no control method is currently available that would allow appropriate modulation of the VSTA I during use. The original VSTA I prototype was found to be limited for testing. The height of the VSTA I made subject recruitment difficult, particularly for amputees with longer residual limbs, and its mass was deemed unsatisfactory for long duration testing [10,11].

The VSTA II is an updated prototype of the VSTA I created for advanced testing of variable transverse plane stiffness in lower limb amputees. This paper outlines the advances of the VSTA II over its predecessor and how these advances will benefit future human subject studies.

2. Design concept

The VSTA II retains the original VSTA I functional concept, but is a completely new design. The VSTA I utilized a variable length lever arm to produce an infinitely variable stiffness range between 0.12 and 0.91 Nm/° in addition to a completely locked condition. The VSTA II design uses five torsion springs in parallel that can be combined to create five discrete stiffness settings plus an additional locked setting, for a total of six operating modes.

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Fig. 1. VSTA II (purple) installed in pylon with control system attached to socket. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The VSTA I required tethered operation, limiting its use to in-lab testing only. Design of the VSTA II included a stand-alone power and control system allowing operation both in and out of the lab. Design of the VSTA II was completed in two phases. First design of the physical device, and second, design of the controller.

2.1. Device design

Design of the physical VSTA II mechanism utilized the same functional requirements of the VSTA I, with the primary driving factor being installation in the pylon of an existing prosthesis (Fig. 1). The VSTA II prototype consists of two main housings that provide support to the internal components (Fig. 2-I, A and B). A central shaft (Fig. 2-I, C) coordinates movement between the internal components and is supported by bushings in each housing (Fig. 2-I, D and E) along with a needle roller thrust bearing (Fig. 2-I, F), both reducing friction when loaded. The shaft is rigidly attached to a central gear (Fig. 2-II, G). The central gear meshes with gears on the five subunits (Fig. 2-II, H1–H5), discussed in detail later. Each subunit is supported by a bushing in the upper housing and a pin in the lower housing (Fig. 2-I, I and J) and encompasses a spring (discussed later) that reacts against the housing via the ground bar (Fig. 2-I, K). Fully locked operation is facilitated by a solenoid operated key (Fig. 2, L) that locks the male pyramid adapter (Fig. 2-I, M) to the upper housing. A female pyramid adapter (Fig. 2-I, N) is built directly into the lower housing facilitating a lower build height compared to a standard bolt-on adapter. Lastly, an internal rotation sensor (Fig. 2-II, O) meshes with the gear set and allows for displacement feedback during operation.

The function of the VSTA II utilizes torsion springs combined in parallel to create discrete stiffness settings that can be selected during operation. The five subunits each consists of a center post and lower force arm bolted together (Fig. 3, A and B), providing the main structure. A torsion spring (Fig. 3, C) wraps around the post and is deflected by either the upper or lower spring pins depending on the direction of rotation (Fig. 3-I, D and E) and reacts against the ground bar (Fig. 3-I, F) which is fixed to the lower housing. Inside the center post is a 5.5-V solenoid (DSTL-0216-05; Delta Electronics, Taipei, Taiwan) that moves a key, modulating the on/off state of each subunit (Fig. 3, G and H). Each spring post has a bushing (Fig. 3, I) that is press fit onto the post, with a location-sliding fit into the center bore of the gear (Fig. 3, J) and into the upper housing (Fig. 2-I, A). The key is grounded to the center post via a slot, with a matching notch in the bottom of the gear. When the key is in the up position (pictured in Fig. 3) the gear is locked to the center post and the subunit is engaged. When the solenoid is powered, and the key is drawn down, the gear is not engaged with the center post, and turns freely without moving the subunit. Lastly, a small insert houses a sensor that indicates when the position of the key is down (Fig. 3-II, K).

To function equally for individuals with either a left or right limb amputation, the VSTA II must operate in both the clockwise (CW) and counter-clockwise (CCW) rotation directions, however, torsion springs experience high stresses when deflected against the wind of the coils [13]. The setup of the subunit allows for bidirectional movement, while only deflecting the springs in the direction of the coil winding. If the spring post rotates CW about its axis (Fig. 4 from the top down), the upper spring pin in the center post will move to deflect the upper tang of the torsion spring while the lower tang is held in place by the ground bar. Conversely, if the spring post rotates CCW, the lower spring pin in the force arm moves to deflect the lower tang of the torsion spring while the upper tang is held by the ground bar. In this way, the torsion spring achieves bi-directional movement while only deflecting the spring in the direction of the coil wind.

The driving factors for the design of the VSTA II were reduction in height and mass. The axial space available for the addition of prosthetic components depends on an amputee's residual limb length. Reductions in VSTA height allows for fitment on a greater number of individuals, increasing subject recruitment potential. Additionally, the VSTA I had a mass of 1.8 kg. While it has been shown that this amount of additional mass does not have a significant effect on amputee self-selected walking speed or metabolic cost [14–17], all subjects from the initial VSTA I study commented on the mass and noted that it would not be suitable for extended, daily use [11]. Functional requirements of the VSTA II mirrored the VSTA I. Existing TRA devices range in stiffness from 0.5 to 0.7 Nm/° with deflection of ±30°. The human ankle has a maximum stiffness of approximately 0.8 Nm/° with a maximum deflection of 20° during internal rotation [9,18]. Testing of the VSTA I was performed between 0.3 and 0.91 Nm/° and so this range was used as a starting point for the VSTA II design, with the same displacement of ±30°. The properties of a torsion spring depend on the diameter of wire, the diameter of the coil, the number of coils free to deflect (active coils), and the wire material. Torsion spring calculations provided by the spring manufacturer resulted in a spring with a wire diameter of 4.32 mm, a coil outer diameter of 29 mm, three active coils, constructed from A-228, music wire steel. This resulted in an estimated spring stiffness of 0.25 Nm/°. Given the five-spring layout and that the springs add linearly in parallel, the VSTA II was estimated to have a stiffness range of 0.25–1.25 Nm/°, modifiable in 0.25 Nm/° increments.

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