Mechanism and Machine Theory 110 (2017) 1–15

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmachtheory

Design of a bioinspired tunable stiffness robotic foot

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ARTICLE INFO

Keywords:
Tunable stiffness mechanism
Bipedal robots
Parallel robotics
Optimization
Robotic foot

ABSTRACT

The human foot is capable of adapting to various diverse terrains, and this function is due, in part, to the foot's capacity of varying its stiffness in different anatomical regions. The purpose of this study is to develop an adaptable robotic foot by emulating the human foot's arch, horizontal tie (the plantar aponeurosis, midfoot ligaments, etc.), and its ability of varying its stiffness. The robotic foot is designed, analyzed, optimized and fabricated as a semi-circular arch with a horizontal tie consisting of a Tunable Stiffness Mechanism (TSM). The active number of coils in parallel/series configuration of concentric helical springs is changed to control the stiffness of the TSM. The arch stiffness and tunable stiffness range were optimized using the epsilon constraint method. Analytical and finite element modeling results closely match the experimental validation of both the tunable axial stiffness behavior of the TSM and tunable bending stiffness of the robotic foot assembly. The results also show that the TSM is capable of varying the potential energy storage at midstance depending on the load or displacement applied. In conclusion, a robotic foot was developed to adapt to various diverse terrains through varying stiffness and therefore potential energy stored at midstance; the potential energy is then available for an elastic rebound and propulsion in the terminal phase of gait. By implementing proper control algorithms, the proposed tunable stiffness robotic foot is capable of real-time adaptations to changing terrains, which may lead to the design and development of more adaptive industrial and bipedal walking robots.

1. Introduction

Humans modulate the stiffness of their feet, legs and arms to perform a wide range of tasks (running, jumping, climbing, gripping, etc.) [1]. This function is achieved by muscles which are natural actuators possessing tunable force and stiffness control [2]. The human foot varies its stiffness in different anatomical regions to achieve an efficient gait and adaptation to various diverse terrains. A gait cycle can be divided into three distinct phases: force absorption phase (heel strike), midstance, and propulsion phase (toe off). To reduce total mechanical energy during a human gait cycle, a portion of kinetic energy is stored in the Plantar Aponeurosis (PA) and midfoot ligaments as potential energy in the form of elastic strain energy during midstance. This energy is later utilized for elastic rebound in the terminal phase of gait [3]. The human foot is commonly described as an arched beam structure with a horizontal tie [4] as illustrated in Fig. 1. The PA, midfoot ligaments and muscles are represented here as a horizontal tie. In this arch structure, compressive stresses observed at the upper posterior surface and tensile stresses at the plantar surface, and the bending of the arch generates a tensile stretch of the horizontal tie. The stiffness of the horizontal tie affects both the stiffness

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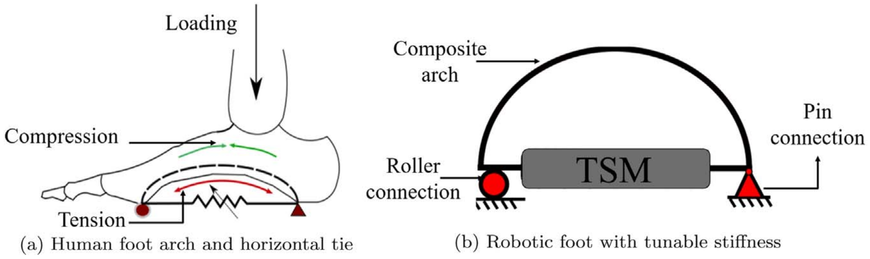
http://dx.doi.org/10.1016/j.mechmachtheory.2016.12.003
Received 2 August 2016; Received in revised form 9 December 2016; Accepted 15 December 2016
0094-114X/



(a) Human foot arch and horizontal tie (b) Robotic foot with tunable stiffness

Fig. 1. (a) Human foot arch and horizontal tie (b) Robotic foot with tunable stiffness.

of the arch structure and the total potential energy stored during midstance.

Current advancements in the field of legged robots stem from the observations of natural walking patterns of humans. These advancements include the improvement agility, obstacle avoidance and performance of legged robots over a wide range of terrains [1]. In this manuscript, we emulate the tunable stiffness function of the human foot to develop an adaptive robotic foot. Instead of classical stiff robotic actuators [2], we will emulate the tunable force and stiffness function of muscles in human feet. It is hypothesized that by varying the foot stiffness, the potential energy storage at midstance can be optimized to minimize the total mechanical energy during a gait cycle.

Tunable Stiffness Mechanisms (TSM's) are mainly used in two major applications: safer robot-human interactions (industrial robots and gait rehabilitation robots) [5–7] and adaptable structural systems (i.e. shock absorption, storage and reuse of mechanical energy) [6,8]. Although for most standard robotic applications, actuators are designed to have a stiff output for better control towards robotic trajectories; many industrial processes also need adaptability in stiffness for applications such as grinding, polishing etc. These operations require tunable stiffness to better adapt to various products with different configurations. Generally, a tunable stiffness setup consists of a passive elastic member, and the stiffness is varied by controlling the equilibrium position [9,10], structure configuration [11,12], antagonistic arrangement [13,14], and mechanical setup [8] of the system. A variable stiffness mechanism is developed by Hollander et al. [15] and it is characterized by the variation of a mechanical impedance by an axial rotation. Gonzalez et al. [11] used a combination of an electrical actuator and an elastic element to obtain a stiffness change. Leaf springs are also used as an elastic member by T. Morita et al. [16] and its effective length is changed by using a sliding mechanism consisting of a motor and a lead screw. Later, Rodriguez et al. [17] developed an antagonistic adjustable stiffness mechanism which consisted of two non-linear springs, and they experimentally validated the design for a large stiffness range and high load magnitudes. Another method in the literature is to vary the length of an elastic element to achieve a stiffness change. Galloway et al. [18] developed and implemented a structural control of a tunable stiffness leg on a hexapedal robot, and this improved the locomotion performance (speed and efficiency) of the robotic system by 40 percent as compared to the baseline robotic system. Recently, a new helical spring based design called the “Jack spring” was proposed by T. Sugar and K. Hollander [19]. This mechanism is characterized by a single helical spring, and the stiffness change is obtained by changing the number of active coils. Ghorbani et al. [20] developed three different conceptual designs of the Adjustable Stiffness Artificial Tendon (ASAT) and studied their dynamics in the ankle joint.

Implementing a TSM in the field of bipedal robots presents new challenges such as size, weight, space and function. Although various designs in multiple industries have been conceived for adjustable stiffness; most of these mechanisms are either heavy, too large, or require heavy motors to drive the stiffness adjustment. Much work is being done in the field of the parallel robotics [21–25] in recent years. The proposed TSM can be used in place of an actuator in parallel robotic systems.

In this research, the variation of the stiffness is achieved by changing the effective structure of a spring. The novel and compact TSM is developed in this research consists of two concentric helical springs with one spring inside and other spring outside. Both springs are fixed at one end and the force is applied on the other end of the inner spring. The tunable stiffness feature is achieved by changing the number of active coils in parallel and in series configurations. This design exhibits a linear force versus displacement response of the spring system for each selected configuration. The conceptual design is further extended analytically with an arch system which mimics the physiology of the human foot during midstance. Many methods are available in the literature for calculating the stiffness of mechanical systems. Among these methods (1) Finite Element Analysis (FEA), (2) Matrix Structural Analysis (MSA) and (3) Virtual Joint Modeling (VJM) are used extensively. FEA is a method to solve real world complex problems by dividing the problem into finite parts called finite elements. MSA is a simplified form of FEA in which beam, truss and frame elements are used to define the system. FEA is typically used for more complex loadings, materials, geometries and/or boundary conditions while, MSA is used for structures that may be described by the deformations of simpler element types. Furthermore, VJM is a further simplification of MSA in which the members are assumed rigid and member deformations are approximated by adding virtual joints between member end conditions [26]. The flexibility method (i.e. the unit load method of virtual work) which is being used in this work is a classical method which may be used to derive the stiffness of members or elements in a stiffness analysis such as FEA and MSA. In the proposed work, the flexibility method is used to derive the relationship between the total stiffness of the system and stiffness of the horizontal tie, and the analytical solution provides computational efficiency when used with optimization algorithms. A Multiobjective Design Optimization (MDO) is performed by using the epsilon constraint method to optimize the design of the TSM with an arch system under a set of defined constraints. The effective tunable stiffness range and energy storage is