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Modelling and Characterisation of Twisted String Actuation for Usage in Active Knee Orthoses ⋆

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Abstract: In active knee orthoses, quiet, powerful, and light-weight actuators are required to support the user during challenging tasks like sit-to-stand and stair climbing. The twisted string actuation concept, based on parallel arranged strings twisted by a small DC motor, is a promising approach to cover the defined requirements. For characterisation of the parallel arranged strings, a test bench is introduced to investigate the transmission and the failure behaviour of the twisted string transmission. The application of different test conditions for characterisation requires a mechanical load which is generated by an additional DC motor and a rope winch. This programmable mechanical load is applied to the strings and measured by a force sensor. A force controller is used to generate a desired mechanical load profile. This paper outlines the mechanical model and the implementation of the mechanical load test bench for the twisted string actuator, and the transmission characterisation.

Keywords: actuator, transmission, characterization, real-time communication, orthoses.

1. INTRODUCTION

Independent mobility in everyday activity is an important asset for young and old people. But that freedom is increasingly restricted due to physiological ageing processes. Reduced muscle strength leads to problems during important movements like sit-to-stand and stair climbing. External support could extend independent mobility. Many stationary facilities are already used to support in daily situations, e.g. wheeled walkers and stair lifts. Intensive research is devoted to develop new solutions to handle the drawbacks of stationary facilities characterized by limited mobility [Herr (2009)].

Active knee ankle foot orthoses (KAFO) are capable to generate a supporting torque in the lower extremities like knee and ankle. The torque is provided by an auxiliary drive connected to the KAFO. As a result of the supporting torque, the users will be able to manage transfer movements like sit-to-stand on their own.

In case of interaction between the user and the external supporting systems, patient safety aspects have to be considered. The interaction forces have to be precisely controlled in order to prevent injuries and enhance comfort in daily activities. Furthermore, the whole system should exhibit a save failure behaviour to avoid a malfunction during transfer movements (e.g. stair climbing).

The state of the art in active orthoses and lower extremities exoskeletons comprises medical and military systems pursuing different strategies and target groups. Compliant actuators like series elastic actuators (SEAs) are frequently used to provide the supporting torque. Some examples are given in [Kong et al. (2010), Pott et al. (2013), Sergi et al. (2012), Zhu et al. (2014), Karavas et al. (2013), Junius et al. (2014) and Pratt et al. (2004)]. These actuators utilize an intrinsic elasticity to realize a save human machine interaction by means of controlling the interaction forces between the user and the active orthoses, given by spring tension measurements. The actuators can be classified as SEAs containing different spring types (see Fig. 1). New approaches introduce actuators with a variable compliances [Rahman (2012), Yu et al. (2011), Tagliamonte et al. (2010)].

Most systems containing SEAs are only able to deliver partial support where the user has to contribute his remaining power for movements. About 30 % extra power of the required power in transfer movements should result in a significant mobility benefit [Samuel and Rowe (2009), Junius et al. (2014)].

Nevertheless, systems containing SEAs are large and heavy and not suitable in daily use. In addition a less favourable centre of gravity impairs the users natural gait and results in instability and increased muscle tension. Small, save, powerful and light weight actuators in lower extremities exoskeletons is a major deficiency.

Alternative concepts including hydraulic [Zoss et al. (2006)] and pneumatic systems [Beyl et al. (2014)] provide large forces and have a small footprint but are not considered in this application due to the requirement of a power source in terms of a compressor or pump that reduces the over-all power density of such actuation systems to an unacceptable level.

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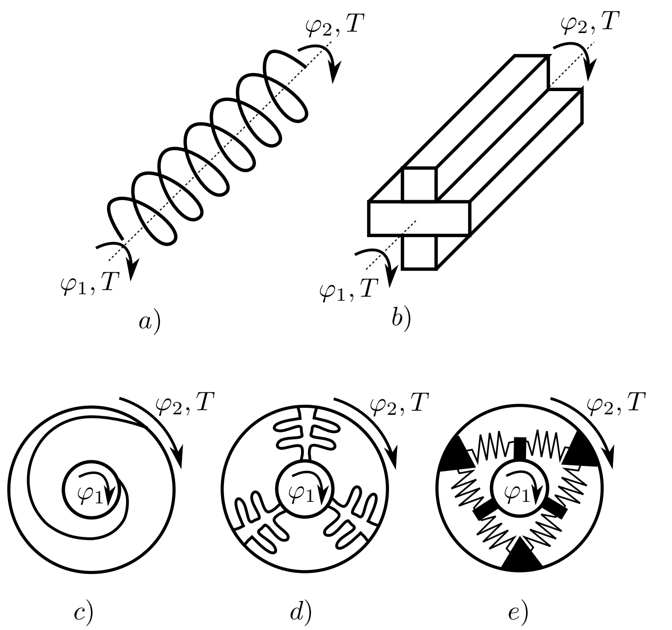

Fig. 1. Possible spring types in SEAs: a) classic torsion spring, b) cantilever spring, c) and d) monolithic structured spring element, e) circular structure with classic springs.

Approaches in actuation of artificial hands [Palli et al. (2013), Sonoda et al. (2012)] and elbow exoskeletons [Popov et al. (2013), Shisheie et al. (2013)] introduces the application of string gears for transmission of rotatory motor movement into linear motion. The string gear is very light weight and shows high transmission ratios. Furthermore, small DC motors of only a few mNm torque are capable of producing forces up to a three-digit range. On the other side the strings are sensitive to external disturbances and have a non-linear transmission behaviour.

This paper focuses on the modelling and characterisation of the string transmission behaviour and the application in lower extremities exoskeletons. For this purpose, it is essential to know the level of efficiency, required motor torque and failure behaviour.

The paper is structured as follows: in section 2 the methods are presented comprising the model of the string gear, the experimental setup, and the control of the overall system. Section 3 deals with the results of transmission measurements while section 4 discusses the application of string transmission in active orthoses and exoskeletons. Finally, section 5 summarises and discusses the findings obtained during the investigation.

2. MODELLING AND CONTROL

2.1 String actuator model

For a geometric modelling of the transmission behaviour, we assume an ideal string with constant diameter $\varnothing_{string} = 2 \cdot R_{string}$ and neglecting the string compliance. Additionally, the number of parallel strings n is defined as $n = 2$. The strings are looped around two shafts of diameter $\varnothing_{shaft}$ in our experimental setup (see Fig 2).

At the start position (Fig. 2 a)) the twisting angle α is zero and the distance between both shafts is given by

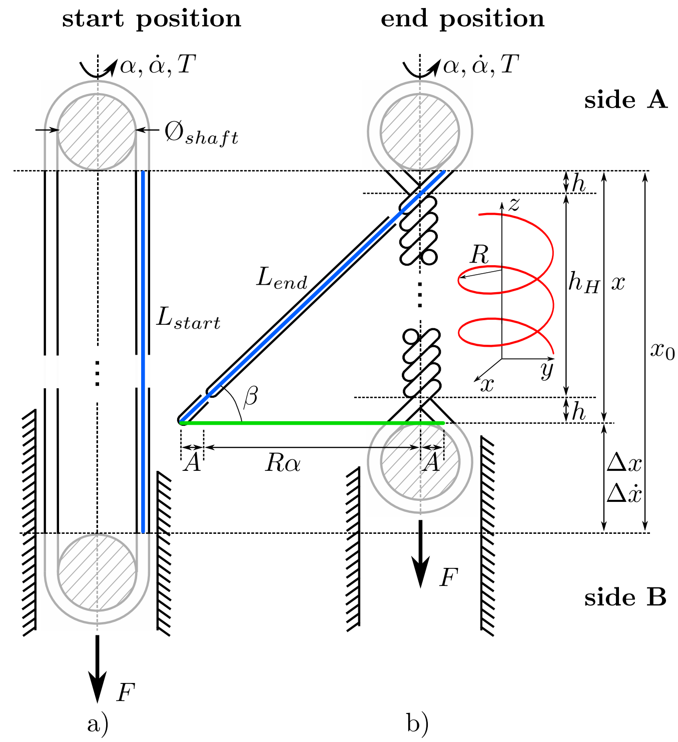

Fig. 2. Model of string transmission: (a) shows the string in its original condition ($\alpha = 0, \dot{\alpha} = 0$ and $T = 0$). (b) is for $\alpha > 0$.

$L_{start} = x_0$. Once side A rotates ($\alpha > 0$), the strings are twisted and cause a contraction of the string gear. The twisted strings form a helix structure with radius R which can be thought in unwound condition as a triangle with hypotenuse L_{end} and adjacent side given by $2A+R\alpha$. Neglecting a larger wrap angle at the fixture shafts in end position and assuming $A < \varnothing_{shaft} \ll L_{end}$ which is true in the actual case of $A < 2\,mm \ll 250\,mm$ one can conclude that

$$L_{end} = L_{start} = L = x_0. \quad (1)$$

In that case the actual position x at the end position is defined by the theorem of Pythagoras as follows

$$x = \sqrt{L^2 - (R\alpha)^2}. \quad (2)$$

Now the contraction Δx is given by

$$\Delta x = x_0 - x = L - \sqrt{L^2 - (R\alpha)^2}. \quad (3)$$

The time derivative results in the following expressions defining the relation between contraction speed $\Delta\dot{x}$ and the rotor angular speed $\dot{\alpha}$ and the required motor torque T and mechanical load F respectively.

$$\Delta\dot{x} = \frac{R^2\alpha}{\sqrt{L^2 - (R\alpha)^2}}\dot{\alpha}. \quad (4)$$

$$T = \frac{R^2\alpha}{\sqrt{L^2 - (R\alpha)^2}}F. \quad (5)$$