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Optimization of stepped-cone CVT for lower-limb exoskeletons☆

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Summary Wearable exoskeletons offer interesting possibilities to address the global concerns of the ageing society and hence many researchers and industries are investing significant resources to develop new innovations in the area of physical assistance. An important issue in providing effective physical assistance is how the needed torques can be generated efficiently and effectively. This paper considers this area and explores the use of continuous variable transmissions (CVT) for up-grading/downgrading torques so that the torque variations for performing motions of normal daily living can be provided. The knee joint is focused upon to develop the key stages of the CVT based approach in generating motion torques. From our on-going research to developing assistive exoskeletons for support activities of daily living it has been found that 6.3—20.6 Nm torque is required to provide 10—20% assistance at the knee joint of a healthy elderly person having weight 70—90 kg. The challenge here is to miniaturize conventional CVTs developed for the automobiles where large torques are needed. To achieve the required torque range for supporting human joints in various motions, a CVT is designed and its parameters optimized. Results are validated via a professional optimization software.

Introduction

UN population statistics published in October 2015 (UN Population division, 2015) state that the percentage of the elderly in coming decades will rise steeply to nearly 30%. This means, that the real-world solutions related to the problems of elderly need to be addressed quickly and market products need to be made available. In this respect ensuring the personal mobility of elderly persons is a central requirement; it is well known that as we age, many elderly persons cannot move around in a stable manner for normal daily living and this has a serious degradation in health and quality of life. The traditional approach to addressing such mobility issues is to use walkers, crutches, and wheelchairs which can provide some solutions but are not entirely satisfactory due to inherent limitations or the fact that significant

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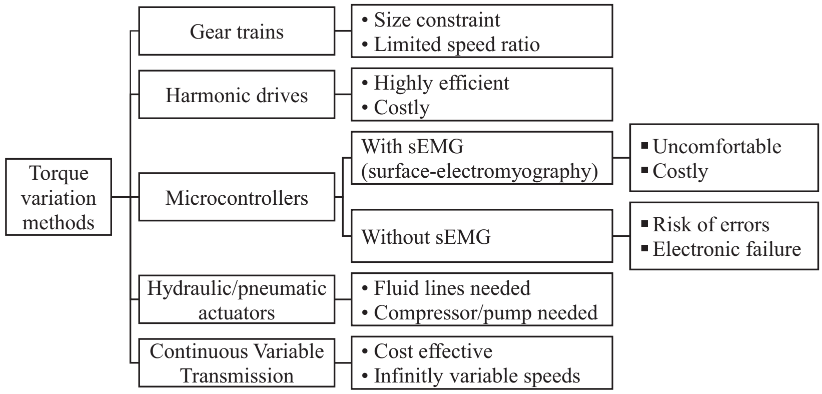

Figure 1 Torque variation methods and key issues for use in exoskeletons.

changes need to be made to the living space (e.g., addition of ramps to replace stairs, etc.). As wearable exoskeletons are designed to fit the human body and support normal body motions, they potentially offer superior solutions.

Hence, the growing interest to develop viable exoskeleton technologies. The research although growing is still largely limited to medical applications such as aiding paraplegics or other patients for or full or partial motion assistance. Assisting healthy elderly persons to continue living independently in their own homes for as long as possible has not been receiving significant attention, such persons need much lower levels of physical assistance. The recently published ISO 13482 safety standard defines a low power physical assistant robot as being able to be overpowered by the human wearer under a single fault condition so no harm can be caused. Although such low powered exoskeletons can provide up to 50% support, we consider even lower levels to assess the viability of CVT technologies to supply 10—20% assistance for various living motions. Collaborations between University of Gävle, Sweden and Thapar University, India are aimed at developing affordable assistive components for wearable exoskeletons. Recently, the authors have carried out a review on lower-limb exoskeletons and exposed the need of developing general purpose assistive exoskeletons for healthy persons (Rupal et al., 2016) and also how the powering issues needing attention (Dhand et al., 2016). Here we continue the investigations into how the needed torques at the joint level can be provided various methods are discussed and the CVT is selected and optimized for delivering the required range of torques.

Torque variation methods

Wearable exoskeletons require actuators to drive the various joints to give the needed motion to limbs; for example rotary or linear electrical motors, hydraulic/pneumatic cylinders are commonly used. The actuators normally provide constant operational speed whereas the motion requirement of human limbs varies for the different motions such as sit-to-stand, walking on flat ground or for stair climbing. Thus, a speed/torque control system is used which allows the appropriate toque to be applied at the required time. The most commonly used methods are presented in Fig. 1 with some issues which are relevant for wearable exoskeletons; it can be seen clearly from the comparison that continuous variable transmissions offer a good potential approach.

Continuous variable transmissions

Continuous variable transmissions or CVTs, are mechanical devices which provide infinite variability in the gear ratio between two finite limits to vary torque as needed. There are different types of CVTs, e.g. belt CVTs (Srivastava and Haque, 2009), toroidal CVTs (Carbone et al., 2004), spherical CVTs (Kim et al., 2002), conical CVTs (Spanoudakis and Tsourveloudis, 2013), etc. A brief comparison between these CVTs is presented in Table 1, which examines the feasibility of CVTs to be installed in exoskeletons.

From Table 1, it is apparent that the cone CVT is a good option for deployment in wearable exoskeletons and should be further explored. Cone CVTs are used with a linear actuator, operated with a controller and a linear actuation mechanism (Spanoudakis and Tsourveloudis, 2013) to obtain

Table 1 Comparison of CVTs.

CVT type	Speed ratio range	Observations
Belt CVT (Srivastava and Haque, 2009)	0.5—2	• Small speed ratio range • Difficult to miniaturize
Toroidal CVT (Carbone et al., 2004)	0.5—2.5	• Complex torus and roller design • Difficult control strategy
Spherical CVT (Kim et al., 2002)	0.2—3	• Problem of slippage • Traction fluid needed
Cone CVT (Spanoudakis and Tsourveloudis, 2013)	0.1—4	• Easy to design and miniaturize • Cost-effective and low number of parts

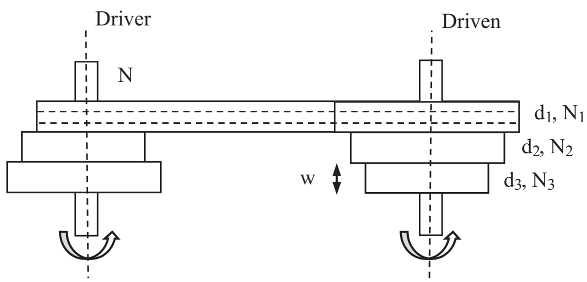

Figure 2 Three stepped-cone CVT.

infinite speed ratios. For exoskeletons, finite speed ratios are sufficient but a large speed ratio is required, which has driven us to use a stepped-cone CVT for realizing the solution needed in an affordable technical design. In this respect a stepped-cone CVT is considered and optimized.

Optimization of stepped-cone CVT for wearable exoskeletons

A three stepped-cone CVT as shown in Fig. 2 is used which will give the user three speed options (low, medium and high), speed steps can also be increased to four or five depending on the requirement, but initially a three stepped-cone CVT is considered. The objective is to optimize a three-step cone CVT which has four design variables i.e. the diameters of the three steps and the width of each step which has to accommodate the belt drive. A three stepped-cone CVT is shown in Fig. 2 and it is assumed that the widths of steps are the same.

Optimal problem formulation

The design vector is taken as:

$$X = [d_1, d_2, d_3, w]^T, \tag{1}$$

where d_i is the diameter of the ith step on the output shaft and w is the step width. d'_i is the diameter of the ith step on the input shaft and ρ is density of step cone. The objective function is taken as weight of the stepped-cone CVT:

$$\begin{aligned} \text{Minimize } f(x) &= \rho w \frac{\pi}{4}\left[d_1^2 + d_2^2 + d_3^2 + d'^2_1 + d'^2_2 + d'^2_3\right] \\ &= \rho w \frac{\pi}{4}\left[d_1^2\left\{1+\left(\frac{N_1}{N}\right)^2\right\} + d_2^2\left\{1+\left(\frac{N_2}{N}\right)^2\right\} \right.\\ &\left.\quad + d_3^2\left\{1+\left(\frac{N_3}{N}\right)^2\right\}\right] \end{aligned} \tag{2}$$

The required torque range of 6.3—20.6 Nm (experimental data) is used to obtain the maximum and minimum speed limits at discrete steps. The torque values for this calculation are taken as 20.6 Nm (low speed), 13.45 Nm (medium speed) and 6.3 Nm (high speed). The input speed, N (from the driving Maxon motor, P = 100 W) is 3490 rpm and the three speed steps after calculations using speed-torque relations ($P = 2\pi NT/60$) are 46, 71 and 151 rpm.

$$\begin{aligned} &= 2700 w \frac{\pi}{4}\left[d_1^2\left\{1+\left(\frac{46}{3490}\right)^2\right\}\right. \\ &\left.\quad + d_2^2\left\{1+\left(\frac{71}{3490}\right)^2\right\} + d_3^2\left\{1+\left(\frac{151}{3490}\right)^2\right\}\right] \end{aligned} \tag{3}$$

Belt should be equally tight on corresponding steps, the overall length of the belt must be kept invariant for all the output speeds. This can be ensured by satisfying the following equality constraints:

$$h_1(x) = L_1 - L_2 = 0, \tag{4}$$

$$h_2(x) = L_1 - L_3 = 0, \tag{5}$$

where L_i denotes belt length (Rao et al., 2011) and is given by:

$$L_i = \frac{\pi d_i}{2}\left(1+\frac{N_i}{N}\right) + \frac{((N_i/N)-1)^2}{4b} + 2b \tag{6}$$

where b is the distance between the shafts axis, taken as 0.1 m.

The constraint for ratio of tensions which usually taken as two units, can be expressed as:

$$g_{1,2,3}(x) = R_i \geq 2, \tag{7}$$

where the tension ratio (R_i) is as under:

$$\frac{T_1^i}{T_2^i} = e^{\mu\theta_i}, \tag{8}$$

where T_1^i and T_2^i are the tensions on the tight and slack sides of the belt, μ is the coefficient of friction, and θ_i the angle of lap of the belt drive. The angle of lap is given by:

$$\theta_i = \pi - 2\sin^{-1}\left\{\left(\frac{N_i}{N} - 1\right)\frac{d_i}{2b}\right\} \tag{9}$$

The constraint for power transmitted is given as below:

$$g_{5,6,7}(x) = P_i \geq 100, \tag{10}$$

where P_i is expressed as: (Rao et al., 2011)

$$P_i = stw\left[1 - \exp\left[\mu\left\{\pi - 2\sin^{-1}\left\{\left(\frac{N_i}{N} - 1\right)\frac{d_i}{2b}\right\}\right\}\right]\right]\frac{\pi d_i N_i}{60} \tag{11}$$

where s is the maximum allowable stress (1.75×10^6 N/m^2) in the belt and t is the thickness of the belt. Finally, the variable bounds are taken as:

$$w \geq 0 \tag{12}$$

$$d_i \geq 0, \quad i = 1, 2, 3. \tag{13}$$

All the values for the various constants used in the formulation of the optimization problem are assumed according to the range of the assistance needed. The optimization problem has ten constraints, which includes two equality and eight inequality constraints. This optimal problem is solved

Table 2 Optimal values of the CVT design variables (mm).

Variable	d_1	d_2	d_3	w
MATLAB function (*fmincon*)	102	70	36	6

by two different methods using MATLAB routines. The complete code is developed in MATLAB environment and the results obtained are presented in ''Results'' section.

Results

The optimized values for the diameters and the width of the three stepped-cone CVT are presented in Table 2. Inbuilt MATLAB function *fmincon* is used for optimization of this non-linear function. These values can be further used for experimental prototyping and validation for use in exoskeletons for healthy elderly.

Conclusions

The growing need for developing assistive exoskeletons for healthy elderly persons has led to this research work. Various torque variation methods used in exoskeletons are surveyed and the need for an affordable technology is raised. A stepped-cone CVT has been investigated and a three stepped-cone CVT design realized for potential use in lower-limb exoskeletons. It is foreseen that such stepped CVTs can be manual operated to select the needed speed ratio as needed.

Conflict of interest

There is no conflict of interest.

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