Mechanism and Machine Theory 92 (2015) 230–239

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Design of a statically balanced fully compliant grasper

A.J. Lamers [a], Juan Andrés Gallego Sánchez [b,*], Just L. Herder [c]

[a] University of Twente, Einschede, The Netherlands
[b] Dept. Mechanical Engineering, Eafit University, Medellin, Colombia
[c] Dept. of Precision and Microsystems Engineering (PME), TUDelft, Delft, The Netherlands

ARTICLE INFO

Article history:
Received 20 February 2015
Received in revised form 15 May 2015
Accepted 25 May 2015
Available online xxxx

Keywords:
Static balancing
Zero stiffness
Pseudo-rigid-body model
Compliant mechanisms
Laparoscopic grasper
Rigid-body-replacement-method

ABSTRACT

Monolithic and thus fully compliant surgical graspers are promising when they provide equal or better force feedback than conventional graspers. In this work for the first time a fully compliant grasper is designed to exhibit zero stiffness and zero operation force. The design problem is addressed by taking a building block approach, in which a pre-existing positive stiffness compliant grasper is compensated by a negative stiffness balancer. The design of the balancer is conceived from a 4-bar linkage and explores the rigid-body-replacement method as a design approach towards static balancing. Design variables and sensitivities are determined through the use of a pseudo-rigid-body model. Final dimensions are obtained using rough hand calculations. Justification of the pseudo rigid body model as well as the set of final dimensions is done by non-linear finite element analysis. Experimental validation is done through a titanium prototype of 40 mm size having an unbalanced positive stiffness of 61.2 N/mm showing that a force reduction of 91.75% is achievable over a range of 0.6 mm, with an approximate hysteresis of 1.32%. The behavior can be tuned from monostable to bistable. The rigid-body-replacement method proved successful in the design of a statically balanced fully compliant mechanism, thus, widening the design possibilities for this kind of mechanism.

1. Introduction

In this article the use of the pseudo-rigid-body-model (PRBM) is shown for the first time in the design of a statically balanced fully compliant grasper. The design and development of a true monolithic prototype are proved valuable in the development of a grasper for minimal invasive surgery. Minimal invasive surgery is a technique in which surgeons access the body cavities by small incision rather than large ones. In this kind of surgery tissue manipulation is carried out by laparoscopic instruments. The instruments besides tissue manipulation, supply the surgeon with sensory feedback. More specific for the grasping instruments, tactile information is provided as force feedback between the input and output of the instrument mechanism. Important design requirements for surgical tools are high force feedback and high sterilizability. Ideally, sterilizability means removing all hinges which are present in conventional tools based on rigid body mechanisms. This can be done by designing a fully compliant grasper. But then elastic stiffness will disturb the force feedback. Statically balanced fully compliant mechanism can cope with these design requirements by providing design possibilities for cheap disposable tools due the monolithic character of fully compliant mechanisms.

In 1997 the urge for high force feedback was recognized and aimed for by designing a rolling contact mechanism replacing the conventional hinged surgical grasper by Herder et al. [1]. In 2000 it was realized by Herder and van den Berg [2] that friction, wearing, and lubrication could be eliminated by moving towards a zero stiffness compliant design, with the added benefits of sterilizability and reduced assembly costs. While a prototype was made, it was not a fully compliant design, it consisted of a 43 N/mm positive stiffness

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* Corresponding author.
E-mail addresses: toonlamers@hotmail.com (A.J. Lamers), jgalleg5@eafit.edu.co (J.A. Gallego Sánchez), j.l.herder@tudelft.nl (J.L. Herder).

http://dx.doi.org/10.1016/j.mechmachtheory.2015.05.014

compliant gripper compensated by a rolling contact mechanism. The balancing mechanism compensates for the elastic forces of the compliant grasper. Later in 2004 Stapel and Herder [3] proposed a feasible solution for a fully compliant version but no prototype was made. De Lange et al. [4] proposed in 2008 a design based on topology optimization, without a proving prototype. In 2009 Tolou and Herder [5] developed a mathematical model for partially compliant bistable segments in order to facilitate the design of a partially compliant balancing mechanism. In 2010 fully compliant balancing segments (negative stiffness building blocks) were introduced by Hoetmer et al. [6]. A prototype was created using these segments but exceeded the yield stress due to the preload force. As known by the authors no successful prototype has been presented yet of a statically balanced fully compliant surgical grasper.

Fully compliant mechanisms are monolithic structures that gain their motion only from the deformation of their constitutive elements — no relative motion between elements due to sliding or rolling kinematic pairs. Compliant mechanisms have benefits such as the absence of sliding friction wear, noise, vibration and the need for lubrication [7]. However, since compliant mechanisms rely on the elastic deflection of its elements, potential energy is stored as strain energy which introduces stiffness affecting the input–output relationship.

The design of compliant mechanisms is based on three main approaches (i) the rigid-body-replacement, (ii) topology optimization [8] and (iii) the building blocks approach [9,10]. In this work we focus on the rigid-body-replacement method [11,12] since it is a straight forward approach, which takes a conventional rigid body mechanism and replaces the overlapping joints by monolithic flexures. The joint replacement procedure makes extensive use of the pseudo-rigid-model (PRBM) which allows finding a rigid-body mechanism with torsion springs that emulates the behavior of a constant cross-section compliant member undergoing large, nonlinear deflections [13].

The rigid-body-replacement method is a rule-based method that allows the designer to keep control over the topology and the stiffness of the flexure joints which is critical if static balancing is to be achieved [14]. Static balancing is a conservative state of motion where the total potential energy is kept constant along the range of motion, which results in a constant static equilibrium of all the internal forces. A mechanism in such a state does not require any force for its actuation besides those to overcome the inertial loads and non-conservative forces such as friction.

Statically balanced compliant mechanisms can be design be reintroducing into the energy stream between input and output, the stored strain energy in the compliant members from another source of elastic potential energy. The latter can be achieved by combining two blocks with opposite or additive inverse stiffness functions [14]. In our case the compliant gripper exhibits a linear stiffness function which is compensated by a balancer with the same negative linear stiffness function.

In the following, the conceptual design and dimensioning of the balancer is presented. Next the validation of the concept is presented by the use of finite elements analysis and the experimental validation of the prototype. In the conclusion chapter assessment of the design criteria and the design approach will be done. The discussion chapter focuses on the recommendations and perspectives of the obtained design as well as the design approach.

2. The grasper

In this work the grasper design presented in [2] is used. This design was manufactured of orthopedic stainless steel and exhibited a linear positive stiffness of 43 N/mm. Such stiffness value will not be considered since in this work the prototype is manufactured of titanium. Dimensions will be kept but the stiffness will be measured in the prototype.

3. The balancer

The balancer has the function of providing a balancing force function with linear negative stiffness opposite to the positive stiffness of the compliant grasper. To simplify the stiffness calculations a building block approach is used. In this approach the desired total force-displacement function (continuous zero force) from the whole system, is decomposed into two additive inverse functions. Here, each function corresponds to each of the building blocks, one block represents the grasper while the other represents the balancer. Since the force-displacement function of each block is designed a priori and independently, when both building blocks are connected, there cannot be unaccounted sources of stiffness. The latter means that the balancer must be connected to the grasper without any relative motion — no kinematic pairs. A way to connect the two building blocks without relative motion between them is through the use of a straight line guidance mechanism. Hence, the balancer is designed from a slider–rocker linkage with torsion springs at its three joints to account for the elastic stiffness of its monolithic version, see Fig. 1.

For this kind of linkage the force-displacement function $F_{Cx} = f(\Delta x_C)$ can be explicitly found at point C. A study is conducted to determine the influence of the design parameters on the stiffness function. The design parameters are set as the link lengths l_1 and l_2, the stiffness k_A, k_B, and k_C of the torsion springs, the pre-loading deflection Δy_A of point A, the initial position $(0, y_A)$, $(x_C, 0)$ of points A and C respectively, and the preloading of the torsion springs θ_2^0, θ_3^0, and φ^0.

The horizontal force at point C for motion under quasi-static condition can be found from the system of equilibrium equations, see Fig. 2. From link 1 reaction f_{B_y} is expressed in terms of reaction f_{B_x}. From link 2 reaction f_{B_x} is solved. Reaction f_{B_x} is equal in magnitude to force F_{C_x} which yields,

$$F_{Cx} = \frac{l_1 \cos\theta_2 (M_B - M_C) - l_2 \cos\theta_3 (M_A + M_B)}{l_1 l_2 \sin(\theta_3 - \theta_2)} \tag{1}$$