Design of a wearable haptic device for hand palm cutaneous feedback

Mihai Dragusanu
University of Siena
DIISM
Siena, Italy
dragusanu@diism.unisi.it

Alberto Villani
University of Siena
DIISM
Siena, Italy
villani@diism.unisi.it

Domenico Prattichizzo
Italian Institute of Technology,
Torino, Italy
University of Siena, DIISM
Siena, Italy
d.prattichizzo@unisi.it

Monica Malvezzi
University of Siena
DIISM
Siena, Italy
monica.malvezzi@unisi.it

Abstract—This paper presents the design and prototyping of a novel haptic device for cutaneous stimulus of hand palm. This part of the hand is fundamental in several grasping and manipulation tasks, but is still less exploited in haptics applications than other parts of the hand, as for instance the fingertips. The proposed device has a parallel spring-tendon-based mechanical structure and it is actuated by three motors positioned on the hand back. The device is able to apply forces with components both normal and tangential to the palm surface. Furthermore, it can render the contact with surfaces with different slopes and simulate the contact with different surface curvatures, thanks to modular, interchangeable end-effectors. The device has been developed taking into account the biomechanics of the hand. The overall structure of the device is inspired by previous works on fingertip devices, however, the larger size of the palm and the higher forces require a more accurate analysis of the device from the structural point of view.

Index Terms—wearable haptic device, palm stimulation, mechanical design, finite element method

I. INTRODUCTION

Nowday interesting applications of haptic technologies are present in several application fields, as for instance telemedicine and in tele-rehabilitation. Some of these applications have become particularly significant in since the beginning of the past year, when the pandemic situation required solutions for guaranteeing social distance and reducing human/human physical contacts. The hand palms are some of the primary interfaces connecting humans and the surrounding environment, however, fewer devices are developed specifically for the palm [1] with respect to other parts of the body, although studies as the one presented by Klatzky and Lederman’s demonstrated that the hand-closing task depends on haptic information in the palm [2]. Interesting works in this field are presented in [3]–[5].

The device presented in this work (Figure 1) is able to stimulate a large area of the palm with a limited number of actuators (three) and a tendon driven transmission, therefore assuring a good wearability. Various contact interfaces, having different shapes, can be easily connected and disconnected to/from the device to reproduce a tactile sensation more similar to the desired stimulus in different tasks. The kinematic structure of the device is inspired from a family of wearable devices that we developed for fingertip stimulation [6], however, the solicitation of hand palm presents several different challenges.

Fig. 1: Haptic palm prototype and some magnetic modules.

II. HAPTIC PALM

The device consists in a glove instrumented with a 3D-printed parallel structure composed by two main parts, one on the back of the hand, and the other below the palm defined as the end-effector of the device. The part on the hand back consists of a mechanical support for the motors (MG-90S microserves), a microcontroller Elegoo Nano V3+ (ELEGOO Inc, CHN), and a 5V LiPo battery (indicated with A in Figure 2). Three tendons are routed in three paths extruded from the support, arranged to achieve an equilateral "Y-shape". The tendons transmit the forces applied by the motors, through the pulleys, from the back of the hand to the device’s end-effector (B) and therefore to the hand palm. The end-effector is composed of two platforms (D) and (C). The first is connected to the actuation system through the tendons, while the second is connected to the back part by means of rigid link (E). The two platforms are connected by an elastic element (a spring with stiffness coefficient $K_s = 6.7N/mm$, I) that allows the tip-palm disconnection when no forces have to be applied. The rigid link connecting the two main parts (G, F, E) is telescopic to adapt the device dimension to anthropometric dimension of the user hand, and can be rotated through two revolute joints (J1, J2), with the aim to temporary move away the end-effector from the palm without remove the device. Each end-effector module (H) is manually interchangeable to transmit...
the sensation of touching several objects. This are connected to device through magnetic clip and “T-shape” socket.

a) Modelling: The device can be considered as a cable driven parallel robot. Two main reference frames can be defined: the first one \( \mathcal{A} = \{O_A, u_1, u_2, u_4\} \) is fixed on the device body on the hand back, while the second one \( \mathcal{B} = \{O_B, v_1, v_2, v_3\} \) is fixed on the mobile platform in contact with hand palm. In stationary conditions, the sum of the forces and torques (wrench) applied to the platform through the wires is balanced by the forces and torques (wrench) due to the physical contact with the finger pad as follows:

\[
\begin{align*}
\sum_{i=1}^{3} f_i + f_{OB} + f_s &= 0 \\
\sum_{i=1}^{3} \tau_i + \tau_{OB} + \tau_s &= 0
\end{align*}
\]

we indicate with \( f_i \in \mathbb{R}^3 \) the forces applied by the cables, with \( \tau_i \in \mathbb{R}^3 \) the corresponding momentum, with \( f_{OB} \in \mathbb{R}^3 \) the reaction force applied by the hand palm to the platform, with \( f_s \in \mathbb{R}^3 \) the force due to spring deformation, with \( \tau_{OB} \in \mathbb{R}^3 \) the reaction torque and with \( \tau_s \in \mathbb{R}^3 \) the torque due to spring deformation, both expressed w.r.t. \( O_B \) point. Expanding the equilibrium equations we get in matrix form:

\[
\begin{bmatrix}
u_{f_1} & \nu_{f_2} & \nu_{f_3} \\ b_1 \times u_{f_1} & b_2 \times u_{f_2} & b_3 \times u_{f_3} \end{bmatrix} \begin{bmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{bmatrix} + \begin{bmatrix} f_{OB} + f_s \\ \tau_{OB} + \tau_s \end{bmatrix} = 0
\]

where \( b_i \) is the point where \( i \)-th tire is interconnected to the mobile platform, \( \rho_i \) is the tension cable \( i \), and \( \nu_{f_i} \) is the unit vector representing the cable direction.

b) Finite elements method analysis: A structural stationary finite elements method (FEM) analysis was carried out for evaluating the overall stress/deformation of the device in four different loading cases representing typical operative conditions. The materials of the components considered in the simulations are the same of the prototype, i.e. ABS for all the components of the device except for the spring, realized in steel. A first series of simulations analyze the behavior of the device when different force combinations are applied, while a second one investigates the response of the device when the skin elasticity is saturated, i.e. when the end-effector is fixed. In general, results from the FEM analysis (Figure 3) show that the mechanical structure of the device can resist to the forces that are applied in haptics applications, the rigid link and the base of the spring are most stressed parts of device.

III. Conclusions

This work introduces a spring-tendon driven wearable haptic device for hand palm cutaneous stimulation. Its design is based on biomechanical structure of the palm and the need of wearability, reducing dimensions (104 x 81 x (97 ± 7)mm) and weight (89.92g). Future developments of this study will include the validation of forces provided by device, a shape optimization of critical parts, and the development of active modules with sensors and/or multisensory actuators to coupling cutaneous and kinesthetics stimuli.

REFERENCES

[1] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo, Wearable haptic systems for the fingertip and the hand: taxonomy, review, and perspectives, IEEE Transactions on Haptics, vol. 10, no. 4, pp. 580–600, 2017.

[2] S. J. Lederman and R. L. Klatzky, Hand movements: A window into haptic object recognition, Cognitive psychology, vol. 19, no. 3, pp. 342–368, 1987

[3] R. Kovacs, E. Olef, M. Gonzalez Franco, A. F. Sui, S. Marwecki, C. Holz, and M. Sinclair, Haptic pivot: On-demand handhelds in vr, in Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology, 2020, pp. 1046–1059.

[4] X. de Tinguy, T. Howard, C. Pacchierotti, M. Marchal, and A. Le Cuyer, Weatavix: Wearable actuated tangibles for virtual reality experiences, in Haptics: Science, Technology, Applications, I. Nisky, J. Hartcher-O’Brien, M. Wiertlewski, and J. Smeets, Eds. Cham: Springer International Publishing, 2020, pp. 262–270.

[5] D. Trinitatova and D. Tsatevichkou, Deltatouch: a 3d haptic display for delivering multimodal tactile stimuli at the palm, in 2019 IEEE World Haptics Conference (WHC). IEEE, 2019, pp. 73–78.

[6] F. Cinelillo, M. Malvezzi, D. Prattichizzo, and C. Pacchierotti, A modular wearable finger interface for cutaneous and kinesthetic interaction: control and evaluation, IEEE Transactions on Industrial Electronics, vol. 67, no. 1, pp. 706–716, 2020.