This paper appears in the proceedings of the International Conference EuroHaptics 2014

Perceptual evaluation of the passive/active torque and stiffness asymmetry of a hybrid haptic device

Carlos Rossa*, Margarita Anastassova, Alain Micaelli, and José Lozada

CEA, LIST, Sensorial and Ambient Interfaces Laboratory
91190 Gif-sur-Yvette, France
rossa@ualberta.ca; {margarita.anastassova, alain.micaelli}@cea.fr;
joselozada@uti.edu.ec

Abstract. Hybrid haptic interfaces combining brakes and motors can present dissimilar torque and stiffness capabilities when dissipating or restoring energy. This paper aims at identifying the asymmetry thresholds that lead to an alteration in the perception of elasticity simulated by such devices. 17 subjects took part in an experiment consisting in interacting with virtual springs with either controllable stiffness or torque asymmetry levels, and identifying if the springs were symmetric or not. Experimental results indicate that when the decompression stiffness or torque were less than 80% and 60% of the compression stiffness or torque respectively, users did not perceive the asymmetry in 80% of trials. This suggests that hybrid devices can present dissimilar active/passive torque or stiffness capabilities without affecting the perception of elasticity.

Key words: Hybrid actuators, stiffness discrimination, haptic interfaces, perception thresholds, active/passive actuators.

1 Introduction

Understanding human perceptual mechanisms is a key point to guide the design of high performance haptic interfaces. Three commonly used psychophysical tasks to evaluate haptic interaction are stimuli detection, discrimination and identification. Detection deals with the smallest human perceptible kinaesthetic stimulus. Discrimination thresholds reveal the minimal difference in the intensity of two stimuli that leads to an alteration in perception. Identification refers to the human ability to categorize dissimilar parameters. The integration of these characteristics will make the resolution of such devices in terms of force, bandwidth, and displacement, adapted to human perceptual kinaesthetic thresholds.

In the case of a haptic device, a particular concern is the system's ability to generate virtual stiffness since object surfaces that are supposed to be rigid are usually modelled as passive elements with some stiffness and damping. Three

* Corresponding author. Current address: Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB, Canada T6G2V4.

sequential perceptual components constitute the basic percept of a rigid surface, i.e. the initial contact, the static interaction and the final release [1]. A damper or spring can effectively render the initial contact with the surface, but the dynamic interaction and release require a spring model. The perception of stiffness is presumably based on the perception of both force and displacement. Past studies using the discrimination paradigm established a resolution of 5-10% for force magnitude [2] and 13% for torque [3]. For stiffness magnitude identification in the range of 0.2-3 N mm^{-1}, users were able to correctly identify 2.8 stiffness [4]. In [5], users were able identify only 2 levels of stiffness among 5 levels ranging form 0.2 to 5 N mm^{-1}.

In order to improve the range of achievable stiffness, the combination of passive and active actuators has emerged as an effective, user-friendly and stable solution [6][7]. The passive actuator can display high levels of stiffness and torque while the active actuator can only restore a fraction of the dissipated energy. Thus, the effects of this asymmetry in the perception of stiffness must be considered further. To the best of our knowledge, no data exists on the human ability to perceive asymmetry originating from torque or stiffness difference while interacting with a hybrid device. Therefore, the goal of this study is to analyse the user's capability to identify asymmetry in the simulation of virtual springs using a custom-designed haptic device based on a motor/brake actuator pair.

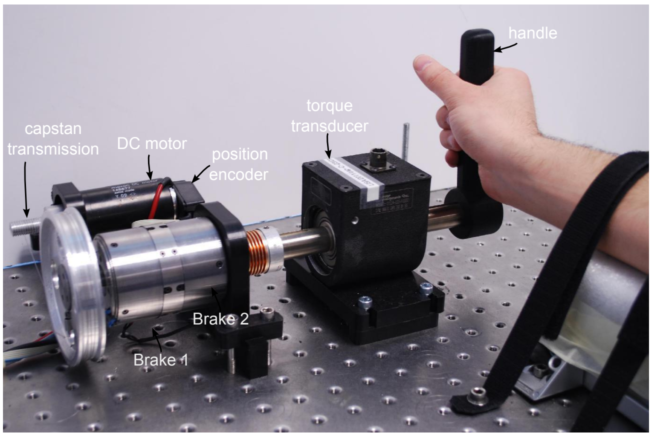
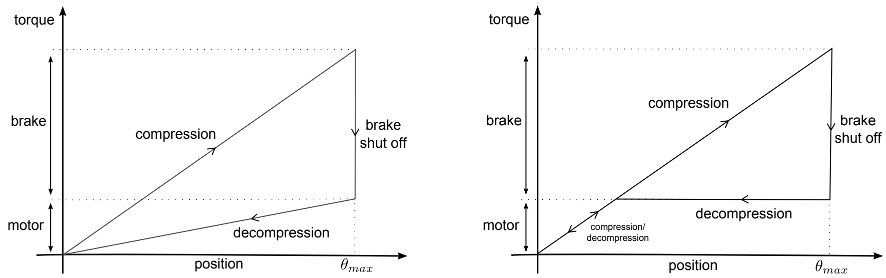


Fig. 1: Experimental setup. The device is composed of two unidirectional brakes [6][8] connected to the handle and a motor linked to a 7:1 capstan transmission. Each actuator can apply up to 1.2 N m monitored using a torque transducer. The shaft's position is measured using a 500 ppr encoder. The participant's arm is stabilized in the mount to clasp the handle in the vertical position.

2 Methodology

In this study the device simulated helical springs with controlled levels of asymmetry. Users were requested to interact with the springs and identify if it reacted with the same torque or stiffness during compression and decompression phases.

Apparatus: The haptic device is presented in Fig. 1. The reference torque of each actuator was calculated by a Silabs C8051F120 microcontroller at 5 kHz and iy was controlled using a closed-loop analog proportional-integral regulator in order to simulate the environments shown in Fig. 2. The necessary torque to turn the handle was proportional to its angular position according to the simulated spring stiffness. When the user compressed the spring, both the brake and the motor could be engaged. During the relaxation phase, the device applied a torque in the direction of motion and the brake was turned off.



(a) Asymmetric stiffness (b) Asymmetric torque

Fig. 2: Asymmetric active/passive stiffness (2a) and torque (2b) environments used in the experiment. θ_{max} is the defined maximal angular displacement.

Environments: In the simulated environments the reference torque was equal to the position times the spring stiffness constant. Two environments were used. **(1)** For asymmetric stiffness (see Fig. 2a) when the user compressed the spring the reaction torque was the sum of the brake and of the motor's torque following the first slope. If the user turned the handle back, the brake was turned off and torque was applied by the motor according to the decompression stiffness. The contribution of each actuator defined the asymmetry ratio. **(2)** For asymmetric torque (see Fig. 2b) the motor simulated the same stiffness during both phases. The asymmetry ratio was generated by limiting the motor's maximal torque. When the motor reached this value, its torque was kept constant and the brake then compensated for the difference in relation to the reference torque. The asymmetry was observed only after the motor had reached its maximal torque. The brake was turned off if the user turned the handle back. When the reference torque was less than the maximal motor's torque, the torque became again proportional to the position.

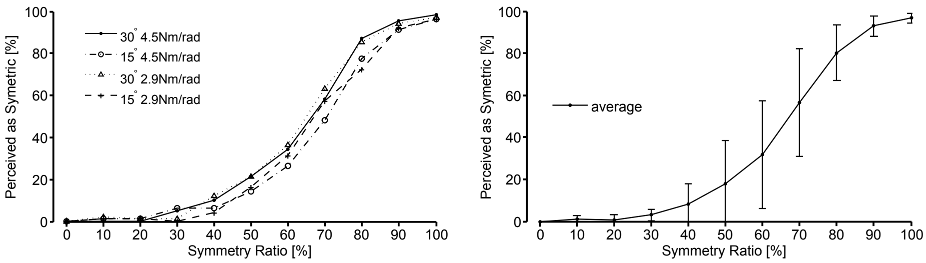
In both cases, 11 levels of symmetry were defined (0%, 10%, 20%... 100%). For symmetry ratio of 100%, only the motor was activated and for 0% only the brake was activated (no force feedback during the decompression phase). Two stiffnesses were defined (4.5 and 2.9 Nm rad^{-1}). The lowest stiffness corresponded to the smallest perceptible stiffness while using the device. In addition, two maximal angular displacements of the handle θ_{max} were defined (15° and 30°). Thus, 44 different environments were composed by the combination of symmetry levels to stiffnesses and displacements.

Participants: A total of 17 participants (4F, 13M) aged from 21 to 32, (average age of 23 years) volunteered to participate in the experiments. All but four were right-handed. None of them had prior knowledge about the device workings. The participants were divided into two different groups of, respectively, 9 and 8 participants. The first group realized tests with asymmetric stiffness and the second group used asymmetric torque environments.

Procedure: The participant was comfortably seated in front of the device and his front arm was stabilized in the mount. The device was hidden and the participants had no visual feedback of their action. They were allowed to get acquainted with the device by interacting with it as long as they desired in a virtual environment with known stiffness and symmetry ratios. A subject then participated in four sets of 110 tests with a constant stiffness and displacement. A set employed one of the four possible stiffness/displacement combinations, within each a symmetry ratio was presented 10 times. The sequence of sets presented to the users was determined randomly. After a set, a break of 2 minutes was given to the participant. In each test, a symmetry level was randomly assigned to the virtual environment. Subjects were instructed to firmly hold the end-effector and to compress the virtual spring and then to turn back to the initial position at most two times. 3° before the end position, a buzzer triggered. The end position was indicated by a second buzzer. The participants were instructed to turn the handle back before the second signal. After each test, they were asked to classify the environment as symmetrical (same torque or stiffness during compression and decompression) or asymmetrical. Each stiffness or torque asymmetry ratios were presented 360 and 320 times respectively, giving a total of 7480 manipulations.

3 Results: Stiffness Asymmetry

Fig. 3a shows the average of environments considered symmetrical, as a function of the stiffness symmetry ratio for each set. The results were equivalent for all four sets. Given the relative standard deviation (see Fig 3b), it cannot be concluded that the displacement or the stiffness have any influence in the perception of asymmetry. For environments with symmetry ratios inferior to 50%, participants perceived the virtual spring as symmetrical only in 20% of the tests. Conversely, for symmetry ratio superior to 80%, on average 80% of the test were considered symmetrical. Since the stiffness during decompression may be lower than during compression, the asymmetric torque presented to the user was changed over the total displacement of the handle. Users were then able to base their discrimination on two aspects, i.e. the torque perceived when they reversed motion, and the torque at initial contact. For low symmetry ratios, the initial torque could be very low and may be imperceptible. Thus, the participants classified the spring as asymmetrical. This may partly explain the low discrimination threshold.



(a) Stimuli perceived as symetric (b) Global average perceived as symetric

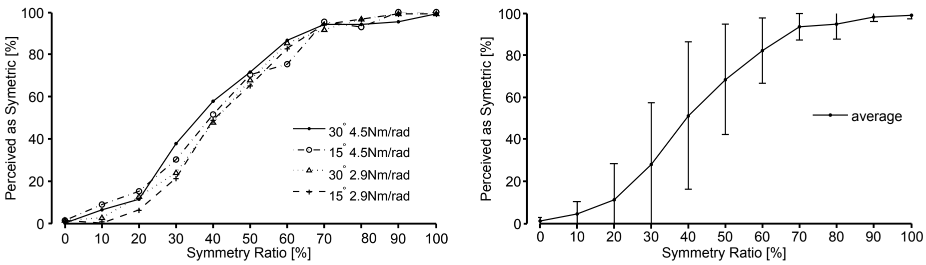
Fig. 3: Stiffness asymmetry results. The rate perceived as symmetric as a function of the symmetry ratio (3a) and the standard deviation for four sets (3b).

4 Results: Torque Asymmetry

As shown in Fig. 4, for torque asymmetry the tendency of the plots is the same whatever the stiffness or the displacement. For a symmetry ratio less than 30%, only 20% of the stimuli were considered symmetrical (see Fig. 4a). Conversely, for symmetry ratios greater than 60%, 80% of environments were perceived as symmetrical. The asymmetry in this case was due to the limitation of the maximal torque. This means that there was a region within the forces that were the same during the compression or decompression phases. For example, consider a symmetry ratio of 50% with a displacement of 30°. Up to 15° the torque in both phases as the same, and torque was only different between 15° and 30°. In contrast to asymmetric stiffness environments, users were not able to base their discriminations on perceived torque close to the initial position. This may partly explain why the discrimination threshold was reduced to 60%.

5 Concluding Remarks

The springs were considered asymmetrical and symmetrical for stiffness symmetry ratios less than 50% and greater than 80% respectively. Using asymmetric torque, these thresholds were shifted to 30% and 60%. The difference can be attributed to the fact that the asymmetry was observed during the total displacement using asymmetric stiffness while for torque asymmetry, the initial



(a) Environments perceived as symetric (b) Global average perceived as symetric

Fig. 4: Torque asymmetry results. The average of tests perceived as symmetric as a function of the symmetry ratio (4a) and the standard deviation (4b).

torque is the same during both exploration phases. These results indicated that users can effectively detect stiffness differences but have more difficulty identifying asymmetry when only the final force was bounded.

The high standard deviation may be due to the random sequence in which the symmetry levels were presented to users. The discrimination can be influenced by the previous stimulus; e.g. a symmetry ratio of 60% tended to be classified as symmetrical when it came after a 20% symmetry ratio. Conversely, users may potentially classify a stimulus as asymmetrical if it followed a symmetry ratio of 80%. In addition, participants expected to perceive more asymmetrical than symmetrical environments. These results suggest that the environment can be perceived as symmetrical by controlling the initial force. This can be integrated in the design of the controller to provide the user with the illusion of elasticity. The device does not need to restore exactly the same amount of energy provided by the operator. This allows the system to combine a small motor and a powerful brake, improving the interaction safety and stability.

References

1. L. Rosenberg and B. Adelstein, “Perceptual decomposition of virtual haptic surfaces,” in *Virtual Reality, 1993. Proceedings., IEEE 1993 Symposium on Research Frontiers in*, pp. 46–53, 1993.
2. X. Pang, H. Tan, and N. Durlach, “Manual discrimination of force using active finger motion,” *Perception & Psychophysics*, vol. 49, no. 6, pp. 531–540, 1991.
3. B. Woodruff and H. Helson, “Torque sensitivity as a function of knob radius and load,” *The American Journal of Psychology*, vol. 80, no. 4, pp. 558–571, 1967.
4. S. Cholewiak, H. Tan, and D. Ebert, “Haptic identification of stiffness and force magnitude,” in *Haptic interfaces for virtual environment and teleoperator systems, 2008. haptics 2008. symposium on*, pp. 87–91, 2008.
5. N. Forrest, S. Baillie, and H. Tan, “Haptic stiffness identification by veterinarians and novices: A comparison,” in *EuroHaptics conference, 2009 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2009. Third Joint*, pp. 646–651, 2009.

6. C. Rossa, J. Lozada, and A. Micaelli, "A new hybrid actuator approach for force-feedback devices," *Intelligent Robots and Systems, 2012. (IROS 2012). Proceedings. 2012 IEEE/RSJ International Conference on*, pp. 4054–4059, 2012.
7. C. Rossa, J. Lozada, and A. Micaelli, "Stable haptic interaction using passive and active actuators," *Robotics and Automation (ICRA), 2013 IEEE International Conference on*, pp. 1050–4729, 2013.
8. C. Rossa, A. Jaegy, A. Micaelli, and J. Lozada, "Development of a multilayered wide-ranged torque magnetorheological brake," *Smart Materials and Structures*, vol. 23, no. 2, p. 025028, 2014.