Design of A Novel Passive Binary-Controlled Variable Stiffness Joint (BpVSJ) Towards Passive Haptic Interface Application

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ABSTRACT In this paper we present the design, development and experimental validation of a novel Binary-Controlled Variable Stiffness Joint (BpVSJ) towards haptic teleoperation and human interaction manipulators applications. The proposed actuator is a proof of concept of a passive revolute joint, where the working principle is based on the recruitment of series-parallel elastic elements. The novelty of the system lies in its design topology, including the capability to involve an \( n \) number of series-parallel elastic elements to achieve \( 2^n \) levels of stiffness, as compared to current approaches. Accordingly, the level of stiffness can be altered at any position without the need to revert to the initial equilibrium position. The BpVSJ has low energy consumption and short switching time, and is able to rotate freely at zero stiffness without limitations. Further smart features include scalability and relative compactness. This paper details the mathematical stiffness modeling of the proposed actuator mechanism, as well as the experimentally measured performance characteristics. The experimental results matched well with the physical-based modeling in terms of stiffness variation levels. Moreover, Psychophysical experiments were also conducted using (20) healthy subjects in order to evaluate the capability of the BpVSJ to display three different levels of stiffness that are cognitively realized by the users. The participants performed two tasks: a relative cognitive task and an absolute cognitive task. The results show that the BpVSJ is capable of rendering stiffness with high average relative accuracy (Relative Cognitive Task relative accuracy is 97.3\%, and Absolute Cognitive Task relative accuracy is 83\%).

INDEX Variable Stiffness Mechanism, Passive Haptic Interface, Psychophysical Tasks

I. INTRODUCTION

Recent research in haptic interfaces has facilitated the advancement of conveying information from remote and virtual environments. The operator’s perception of the conveyed information can be obtained cutaneously (through touch) [1-4], or kinesthetically (through force or torque) [1]. Haptic Interfaces have a wide spectrum of applications, including navigation [5-8], tele-rehabilitation [9, 10], tele-surgery [11, 12], as well as micro-manipulation [13, 14]. Generally, in bilateral teleoperation, an operator can interact with a remote/virtual slave device (robot) through a haptic interface. The haptic interface typically sends the position and velocity commands to the slave device and feeds the registered contact forces back to the operator. Nonetheless, the haptic stimuli, provided by most of the commercially available haptic devices, are still limited to vibrations, reducing the possibility of simulating rich functional contact interactions [15, 16]. Towards more realistic feeling of touching virtual and remote environments, researchers have traditionally focused on grounded haptic interfaces, such as Sigma 7 [17] devices, and glove type haptic displays, such as the CyberGrasp [18].
A haptic interface typically consists of a stimuli, an actuation system, and a control system. From an actuation point of view, haptic interfaces are classified into active, passive and hybrid. An active haptic interface is equipped with actuators (motors) which are capable of adding or dissipating energy from the system. In literature, an extensive number of active haptic interfaces are presented, including the grounded type, such as the PHANTOM [19], and arm exoskeletons [20], as well as wearables, such as haptic gloves [21, 22]. Passive haptic devices, on the other hand, are incorporated with energetically passive actuators, and can hence only dissipate, store or redirect kinetic energy within a system [23]. Energy dissipative haptic devices are intrinsically safe and stable as compared to the active counterparts, but unable to restore energy [24]. By contrast, hybrid haptic devices combine both active and passive actuation, thereby achieving the safety and stability of passive actuators, and the ability to perform energy restitution of active actuators [25]. Both passive and hybrid haptic interfaces incorporate several types of energy dissipative actuators, including electromagnetic dry friction clutches [26], electro-rheological (ER) clutches [27], programmable differential breaks [28], Eddy Current Breaks [29], and MR Brakes [30].

Although energy dissipative (passive) haptic interfaces have the capability of simulating different tasks that include kinesthetic interaction with passive bodies (eg. wall following) [31], they’re not able to fully simulate the interaction with passive elastic bodies. Elastic bodies (Fig. 1a) store energy during compression/elongation, but the direction of the force during the deformation process is always against the direction of motion (Fig. 1b). In this part of the interaction, an energy dissipative haptic device is capable to simulate as it can only generate forces against the motion’s direction. On the other hand, this type of haptic devices cannot simulate the process of releasing as the motion and force share the same direction (fig 1c). To resolve this issue without losing the advantage of passiveness, elastic elements can be integrated within the actuation system of passive haptic interfaces. In this paper, we propose an actuator based on such a design topology. The novel Binary-Controlled Variable Stiffness Joint (BpVSJ) proposed here is to be combined with an upper limb wearable haptic stimuli, towards achieving kinesthetic interactions with the elastic element in a virtual reality environment as shown in Fig 1d.

Realizations of incorporating elastic elements in passive haptic interfaces have been previously reported in literature. In the Elastic Arm [32], elastic cords were applied for obtaining egocentric haptic feedback through body-mounted elastic armature. Fabric stiffness has also been used in cutaneous haptic devices, such as the Bi-elastic fabric softness display [33]. A grounded passive device for real time stiffness display was introduced in [34], while serial elastic actuators (SEA) were used to enhance the closed loop behavior and reduce the output impedance [35]. The main limitations of the SEA lie in its non-optimal performance and non-optimal energy efficiency. Optimal performance requires careful tuning of the joint stiffness values [36]. This has indeed motivated researchers to develop new designs for variable stiffness actuators.

Several topologies and realizations for Variable Stiffness Actuators have been explored in literature. Several research groups investigated the evolutionary concept of antagonistic variable stiffness actuators, where the joint stiffness is varied through the combination of two antagonistic SEAs controlled by two separate motors. Designs that fall into this category include VSA-I [37], VSA-II [38], AMASC [39], and the biological inspired joint stiffness control mechanism [40] and pneumatic muscles [41]. Another realization for stiffness altering is achieved through the principle of lever mechanism. This is accomplished by altering the distance between the pivot and the elastic element or output contact. Examples of this type include the AwAS [42], AwAS-II [43], CompAct-VSA [44], the vsaUT [45], the mVSA-UT [46], the vsaUT-II [47], the HDAU [48] and the pVSI [49]. Further innovative methods that were used to vary the stiffness include altering the number of effective spring coils or “Jack Spring” [50], or altering the effective length of a leaf spring [51 50]. The MACCEPA [52], MACCEPA 2.0 [53] and the DLR FSJ [54] which benefit from a nonlinear connector between the output link and the spring element to adjust the preload of the linear spring. Moreover, other techniques for stiffness variation is introduced. A recent method applies permanent magnets as method of stiffness variation [55].

A more recent approach to vary the stiffness was realized through discretely selecting the level of stiffness by adding/subtracting a number of elastic elements. The elastic elements are engaged through a locking mechanism or simply a clutch/brake., and they can either be arranged in series (the pDVSJ) [56], or in parallel. The realization of the latter is referred to as Series-Parallel Elastic Actuators [57].

The design of Series-Parallel Elastic Actuators (SPEA) was driven by the need to minimize energy consumption, peak
torque, or power consumption in robots and humans [57]. This concept is introduced in the iSPEA [58]. In this actuator, the springs are connected to the output link from one side and to an intermittent mechanism on the other side. This mechanism converts a continuous (rotational) input into two consecutive phases. This yields a succession of springs’ involvement by altering the output torque of the actuator. MACCEPA-Based SPEA is another example of SPEA and is illustrated in [59], where the springs are recruited through a cylindrical cam mechanism. Another illustration is the +SPEA [60]. This actuator benefits from the parallel motors, locking mechanisms and springs to drastically reduce the energy requirement. The previously mentioned examples applied locking mechanism in recruiting springs. Clutches/Brakes were introduced to SEA in Clutched Serial Elastic Actuators towards energy consumption minimization [61]. This concept was extended in the SPEA in [62], where electro-adhesive clutches were integrated in a leg exoskeleton, providing both light-weight and energy efficiency. In this work, the concept of SPEA is being applied in other application (i.e. passive haptics).

In passive haptic interfaces, stiffness can be simulated through variable stiffness joints. This requires (a) a wide range of stiffness to be covered, (b) the capability to change the stiffness at any position without reverting to the initial equilibrium point, and (c) a swift change in the level of stiffness. This has motivated various studies and new designs of variable stiffness mechanisms with passive compliance for haptic applications, such as the pVSJ [49], and pDVSJ [56].

This paper presents, a novel passive variable stiffness joint as a bench-test for further development towards the above proposed haptic devices. The proof-of-concept design demonstrates the ability to vary the stiffness from transparency to high values through changing the number of the associated series-parallel elastic elements. The main contribution of the presented concept lies in its simplicity, scalability, and modularity (capability to involve an (n) number of series-parallel elastic elements to achieve \(2^n\) levels of stiffness. Moreover, the novel joint can rotate freely at the zero stiffness case without limits. Beside the modularity, the contributed design has the ability to directly select the involved elastic element(s) without the need of succession involvement used in the previously proposed designs in literature. The remainder of the manuscript is organized as follows: The concept and design are presented in section II. Stiffness modeling and the dynamic model are detailed in section III. While the physical implementation and experimental results are described in section IV. The psychophysical experiments are illustrated in section V. A discussion to illustrate a comparison between the presented design and the state-of-art designs in literature is presented in section VI. The limitations of the system is being discussed in section VII. Finally, the conclusions and future work are highlighted in section VIII.

II. CONCEPT AND MECHANICAL DESIGN

A. CONCEPT OF THE BPVSJ

The main inspiration behind the design of the BpVSJ is the series-parallel variable stiffness mechanism [58 – 60]. In this type of mechanisms, the stiffness is altered by changing the number of associated elastic elements. The elastic elements are parallel with respect to each other, and their combined stiffness is connected in series with a load (output link) at one end. The other end can be connected in series with a clutching mechanism and an actuator (motor) in an active system. On the other hand, the elastic elements in a passive system can be grounded through controllable locking mechanisms such as clutches/brakes. The new concept is demonstrated in Fig. 2. A brake is serially connected to a torsion spring and then a spur gear, which is then coupled to the main spur gear of the load shaft (Fig. 2a). The brake-torsion spring-gear unit is referred to as a Stiffness Bit, which provides the stiffness of the torsion spring to the main shaft of the load. By connecting n stiffness bits to the main spur gear of the load shaft in parallel, the sum of all the torsion springs’ stiffness will be the output stiffness of the joint as in Fig. 2b. Theoretically, without considering overlapping stiffness results, there are \((n + 1)\) different possible stiffness combination. Here, the number 1 indicates the zero stiffness case, which facilitates the capability of unlimited motion of the output arm at the transparency where all brakes are inactive. In general to obtain \(2^n\) levels of stiffness from n springs in parallel, any combination of stiffness values must be unique. Thus, for a system consisting of three springs, the stiffness of each spring \(K_i\) must follow the following conditions:

\[
K_i \neq K_j \quad i \neq j, \quad \{i,j\} \in \{0,1,2\} \quad (1)
\]

\[
K_i + K_j \neq K_k \quad i \neq j \neq k, \quad \{i,j,k\} \in \{0,1,2\} \quad (2)
\]

FIGURE 2: (a) Stiffness Bit, the set of a grounded brake connected to an elastic element (spring) which would react against the load torque through the gear train. (b) Multiple Stiffness Bits connected to the output link (Load) through combined gear trains.

The key novelty of the BpVSJ lies in the design topology as depicted in Fig. 3. Three custom-made torsional springs with three different values \((K_0, 2K_0, 4K_0)\), respectively, are connected to three brakes, forming three stiffness bits. The combination of stiffness values can be presented through a binary representation based on an active/inactive stiffness bit.
The other end of each spring is connected to a planet gear, which contributes partially to the resultant torque of the sun-gear that is connected to the output arm. An active stiffness bit applies torque on the output arm. If the stiffness bit is inactive, the spring will run freely through a grounded bearing. This will facilitate the capability of unlimited motion of the output arm at the transparency (zero stiffness level) where all the brakes are inactive. The achievable stiffness levels in binary representation are shown in Table I. An active stiffness bit is represented by “1”, while an inactive stiffness bit is represented by “0”. Another advantage of this topology is the modularity or capability of altering the stiffness level at any joint deflection position with very low switching time. Lastly, the scalability can be achieved either by changing the value of $K_0$ or by adding extra Stiffness-Bits.

![Fig. 3: Concept of the BpVSJ; the stiffness is altered by changing number of involved springs.](image)

### Table I: Achievable Stiffness Levels of BpVSJ

<table>
<thead>
<tr>
<th>Stiffness Bit</th>
<th>Stiffness Bit 2</th>
<th>Stiffness Bit 3</th>
<th>Stiffness Bit 4</th>
<th>Stiffness Level</th>
</tr>
</thead>
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<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>$K_0$</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>$2K_0$</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>$3K_0$</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>$4K_0$</td>
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<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>$5K_0$</td>
</tr>
<tr>
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<td>1</td>
<td>0</td>
<td>6</td>
<td>$6K_0$</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>7</td>
<td>$7K_0$</td>
</tr>
</tbody>
</table>

### B. Mechanical Design of the BpVSJ

BpVSJ is designed as a passive haptic interface that is capable to simulate different levels of stiffness in virtual reality and remote environment applications. The desired maximum simulated angular stiffness is 3.5 N.m/degree. This value is selected based on literature to cover a wide spectrum of elastic elements [63], as three Stiffness-Bits are used to simulate seven levels of stiffness. The springs should have the stiffness levels of 0.5 N.m/degree, 1 N.m/degree, and 2 N.m/degree for the first, second, and third stiffness-bit respectively.

Realization of the mechanical system of the BpVSJ can be seen in Fig. 4a. The lower base is fixed and consists of ten bearings that hold 10 shafts. Three of these shafts are connected to three electromagnetic friction brakes. Four shafts are used for the sun-planet gear train, forming a (1:1) ratio for each planet : sun train (depicted as golden gears in Fig. 4b). The three planet gears hold three torsional springs (each gear holds one spring) from below through the spring holders. The last three shafts are used for the two Torque Reduction Stages (TRS). The torque reduction stages are needed to maintain the torque exerted on the brakes lower than the maximum allowable torque of the brake without compromising the maximum desired external torque. These brakes were selected off-the-shelf with maximum torque to size ratio. If the brakes were stronger (with same size), the TRS can be opted. The torque transmission path (red arrow) for each stiffness-bit is shown in Fig. 4c. The torque is transmitted from the user hand through the output link. The output link is connected to a sun gear which transmits the torque to the spring holder through the planetary gear. The torsional spring is connected to two spring holders, which are part of the shafts where the planetary gear and gear from TRS1 are mounted. The first torque reduction stage connects the upper end of the spring holder through 1:2 torque reduction ratio. The second stage of torque reduction (1:2) is transmitting the torque to the brake, resulting a (1:4) torque reduction in total. The arrangement of two stages is selected to minimize the diameters of the lower and upper bases. From the figure, it can be seen that if the brake is active, the output arm will deflect the spring and the user would feel the altered stiffness. If the brake is inactive, the gears will rotate freely and the user would feel no stiffness.

### III. JOINT’S MODELING

#### A. STIFFNESS MODEL

Altering the stiffness of BpVSJ is achieved through changing the number of involved parallel elastic elements. The involvement of an elastic element is achieved through grounding one end of the spring via an electromagnetic brake. The stiffness model will be derived from the kinematics model of the joint illustrated in Fig. 5.

A pushing force (F) exerted by the user’s hand is creating a torque through the arm length (L). The resultant torque ($\tau^r$) will rotate the main shaft with the sun gear. In the case where all stiffness-bits are inactive, the torque and motion will be transmitted freely through the planetary gears, into the torsional springs which they would rotate freely with no compression. In case of any active stiffness-bit(s), the motion of shaft connecting the end of the involved torsional spring to the brake will be blocked. In the presence of the exerted torque on the main shaft, the involved torsional springs will deflect, yielding a counter torque that would be felt as resistance force by the user’s hand.

Deriving the stiffness model starting from the resultant torque ($\tau^r$) equation as follows

$$\tau^r = F \times L = -(\tau^0 + \tau^1 + \tau^2)$$  \hspace{1cm} (3)

where $\tau^0, \tau^1, \tau^2$ are the torque of the stiffness bits 0, 1 and 2 respectively.

Each of these torques can be represented in the following equation:
\[ \tau_n = \beta_n \left( 2^n (K_0) \left( \theta - \phi_n - \varphi \right) \right), \quad n \in \{0,1,2\} \] (4)

\[ \phi_n = \theta(t_{ON,n}), \quad n \in \{0,1,2\} \] (5)

\[ \beta_n = \begin{cases} 0, & \text{if Brake (n) is inactive} \\ 1, & \text{if Brake (n) is active} \end{cases} \] (6)

where \((\beta, \theta, \phi, \varphi)\) are the binary function, joint angular position at the current time, joint angular position at the activation time \((t_{ON})\), and the backlash angle, respectively. The joint stiffness is the rate of change of the torque with respect to the angular deflection.

From the previous equations, the rendered torque \(\tau^\Sigma\) and the total stiffness \(K^\Sigma\) can be derived as follows:

\[ \tau^\Sigma = \sum_{n=0}^{2} \beta_n \left( 2^n (K_0) \left( \theta - \phi_n - \varphi \right) \right), \quad n \in \{0,1,2\} \] (7)

\[ K^\Sigma = \frac{\delta \tau^\Sigma}{\delta \theta} = \sum_{n=0}^{2} \beta_n \left( 2^n (K_0) \right), \quad n \in \{0,1,2\} \] (8)

From (5), it can be concluded that the involvement of each spring is independent from other spring. Hence, the level of stiffness can be altered at any position without the need of reverting to the initial equilibrium point. From (6), it can be concluded that the joint stiffness is dependent on the number of stiffness-bits \(n\) and the base stiffness value \(K_0\). This feature allows the scalability of the model in both the stiffness range and the realized number of stiffness values.

B. DYNAMIC MODEL

BpVSJ is a passive rotary single degree-of-freedom joint that is meant to be used as a passive haptic interface. For haptic interfaces, dynamic models are important to determine the system’s bandwidth and the system’s range of impedance [64]. The dynamic model of the system is assumed to be a simple Inertia-Damper-Spring system and it is written as follows:

\[ I \ddot{\theta} + B \dot{\theta} + K \theta = \tau_h \] (9)

Where \(I, B, K, \tau_h, \theta\) are the moment of inertia, damping coefficient (includes friction damping in gears and between moving parts), stiffness, input (hand) torque, and angular deflection respectively. The stiffness coefficient can be calculated through the stiffness model presented in the stiffness model section.

In order to estimate the inertia and damping coefficients, BpVSJ was subjected to a fixed input torque equalized by the spring tension. From this equilibrium state, BpVSJ is released
and the angular position is recorded. Applying the Nonlinear Least Square Method (Using MATLAB SIMULINK parameters estimation toolbox), all dynamic parameters were estimated empirically. Although the results of least square method are not unique, but it doesn’t affect the purpose of the identification. As the identification results are enhanced through taking several samples and calculating the mean and the variance for these samples. Table 2 illustrates the estimated parameters theoretically and empirically. From the results, it can be concluded that for a system with low speed and acceleration the effect inertia and damping effects will be very low compared to the stiffness coefficient. The bode plot for the system is illustrated in Fig. 6. It can be concluded from the figure that the bandwidth of the system is relatively low and can hence be used for some applications, like haptic exploration tasks [34, 65].

The damping coefficient (B) represents the general friction in the system. Friction occur mainly between the gears during transmission. The damping coefficient effects the minimum rendered torque at the zero-stiffness level. For BpVSJ, the minimum rendered torque at zero stiffness level was approximately 1.2 N.m @ 1 rad/s angular velocity. It’s worth to mention that the Coulomb friction is neglected due to the purpose of dynamic modeling.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>DYNAMICS SYSTEM COEFFICIENTS FOR BpVSJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Estimated Value</td>
</tr>
<tr>
<td>I</td>
<td>0.062±0.02</td>
</tr>
<tr>
<td>B</td>
<td>1.1±0.24</td>
</tr>
</tbody>
</table>

**FIGURE 6:** The bode plot for BpVSJ for all stiffness levels, it can be seen that the bandwidth of the system is dependent on the level of stiffness levels from 1 to 7 and it has the values of (4.7 Hz, 7 Hz, 8.83 Hz, 10.3 Hz, 11.6 Hz, 12.8 Hz, 13.8 Hz) respectively. From these values, it can be concluded that BpVSJ is suitable to be used as haptic interface for exploration applications.

**IV. IMPLEMENTATION OF THE BPVSJ**

The dynamic structure of the BpVSJ consists of ten Stainless Steel A316 shafts (Diameter: 10 mm). The spring capsules were machined as a part of the shafts to eliminate any undesirable slippage. The three torsional springs are made of Stainless Steel A316 (detailed design parameters can be found in Table III, where S0, S1, S2 indicate the springs used in Stiffness Bit 20, 21, and 22, respectively). The springs were calibrated to determine their linear range which is presented in Fig. 7. It is worth to mention that the deviation in S2’s behavior can be due to the human fabrication error as the springs were fabricated in lab. The sun and the three planetary gears are (Misumi GEABBB2.0-25-20-B-10, 25 teeth). The two (2:1) torque reduction stages are composed of six gears (Misumi GEABBB2.0-30-20-B-10, 30 teeth) and another six gears (Misumi GEABBB2.0-15-20-B-10, 15 teeth). The static structure consists of the upper base, lower base and two radial bearing bases made of Aluminum. These bases encapsulate ball bearings to hold the shafts and prevent any buckling due to the shear bending caused by the contact forces of the blocked gears. The base holders are made of Stainless Steel rods (Diameter: 12 mm) and the output link is made of an Aluminum Alloy (300 mm in length).

The sensory system of the BpVSJ includes a force/torque sensor (ATI Mini 40) mounted on the forearm to measure the torque on the output link, a quadrature rotary encoder (RS-260-3768) mounted on the main shaft to measure the output link’s deflection (θ), a National Instrument DAQ (NI-USB-6343), and National Instrument LabVIEW® for real time control and data acquisition (rate of 1000 samples per second). The stiffness bits are activated through the grounded brakes (Mayr 3/520-212.01/24), which are powered by 2-series connected 12 VDC batteries and controlled through Arduino 4-channel Relay Module by the DAQ.

**TABLE III | TORISONAL SPRINGS PARAMETERS**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>S0</th>
<th>S1</th>
<th>S2</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of Spring Wire</td>
<td>5</td>
<td>6</td>
<td>8</td>
<td>(mm)</td>
</tr>
<tr>
<td>Outer Diameter</td>
<td>16.8</td>
<td>18.25</td>
<td>24.2</td>
<td>(mm)</td>
</tr>
<tr>
<td>Inner Diameter</td>
<td>6.8</td>
<td>6.25</td>
<td>8.2</td>
<td>(mm)</td>
</tr>
<tr>
<td>Number of Active coils</td>
<td>5.25</td>
<td>5.25</td>
<td>6.25</td>
<td></td>
</tr>
<tr>
<td>Linear Range (Safe Travel)</td>
<td>7.7</td>
<td>9</td>
<td>2.1</td>
<td>degrees</td>
</tr>
</tbody>
</table>

**FIGURE 7:** Torque vs Deflection of the three springs (S0, S1 and S2)
Experiments were conducted to validate the stiffness model. The characterization test was performed on a horizontal vice (Fig. 8) to eliminate any gravitational potential energy effect. As springs S0 and S1 have a wider linear range than S2. Their individual stiffness levels (level 1 and 2) and combined stiffness level (level 3) are shown in Fig. 10. For the stiffness levels where S2 were involved (level 4, 5, 6 and 7), the linear range is limited to 2 degrees and shown in Fig. 11. It can be seen from both figures that the model is verified in the linear ranges of the springs. The sources of errors can be referred for exceeding the safe travel regions of the springs. As the springs were fabricated in the lab, a slight error in the actual stiffness of the springs is present compared with the desired stiffness (S0: 12.1 %, S1: 2.5%, and S2: 3%). Another source of error can be referred to human error and the different resolutions of the F/T sensor and the encoder (one order of magnitude). As BpVSJ is meant to render stiffness levels, the error will not affect the functionality of the device as a haptic interface for stiffness rendering. Further discussions is illustrated in section V, where the system is validated through psychophysical experiments.

The power consumption of the system depends on the number of active stiffness bits. A single stiffness bit power rate is typically 15 W. Hence, the power consumption can range between 15 to 45 W. It is noteworthy here that the stiffness variation time is same as the on-time of the brake which is 35 ms. Comparing the stiffness variation time of BpVSJ (35 ms) as an example of Discrete Variable Stiffness Actuator to DLR FSJ [54] (300 ms) as an example of continuous variable stiffness actuators, it can be seen that the BpVSJ is one order of magnitude faster than DLR FSJ [54]. This has been achieved with the sacrifice of the continuous stiffness range that continuous variable stiffness actuators like DLR FSJ can achieve. Comparing with the power consumption of BpVSJ (Max: 45 W) to pDVSJ-II [66] (Max. 122.4W) as another example of discrete variable stiffness actuators, it can be seen that BpVSJ has a better power efficiency compared to its counterpart. The power consumption can be minimized through developing lower power consuming brakes, such as MRI based brakes. The design and power parameters of the BpVSJ are illustrated in tables IV and V.

### Table IV: System Design Parameters

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Lower Base Diameter</td>
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<td>mm</td>
</tr>
<tr>
<td>Upper Base Diameter</td>
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<tr>
<td>Output Link Length</td>
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<td>mm</td>
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<tr>
<td>Main Shaft Length</td>
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<td>mm</td>
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<td>Other Shafts Length</td>
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<tr>
<td>All Shafts’s diameter</td>
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<td>mm</td>
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<tr>
<td>Total BpVSJ Length</td>
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<td>Gross Weight</td>
<td>17.9</td>
<td>kg</td>
</tr>
</tbody>
</table>

### Table V: System’s Power and Sensor’s Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Encoder Resolution</td>
<td>0.18</td>
<td>degrees</td>
</tr>
<tr>
<td>Force/ Torque Sensor Force Resolution</td>
<td>0.01</td>
<td>N</td>
</tr>
<tr>
<td>Sampling Rate</td>
<td>1000</td>
<td>Hz</td>
</tr>
<tr>
<td>Single brake Power Rate</td>
<td>15</td>
<td>W</td>
</tr>
<tr>
<td>Maximum Power Rate</td>
<td>45</td>
<td>W</td>
</tr>
<tr>
<td>Stiffness Switching time</td>
<td>35</td>
<td>ms</td>
</tr>
</tbody>
</table>

### Figure 8: The test bed of BpVSJ, the joint is mounted on a horizontal plane table to eliminate the effect of gravitational energy.

### Figure 9: Evaluating Stiffness Levels (Level 1 (red), Level 2 (blue) and Level 3 (black)). The experimental results has proven that the system works for the proposed model at levels 1, 2, and 3. The error can be referred to exceeding the safe travel at deflection 7 degrees for L1, and 9 degrees for L2. The error in L3 can be referred to the different resolutions of F/T sensor and the encoder (Error in stiffness between theoretical and experimental L1: 12.1%, L2: 2.5%, L3: 10.9%).

### Figure 10: Evaluating Stiffness Levels (Level 4 (black), Level 5 (blue) Levles 6 (pink) and Level 7 (red)). The experimental results has proven that the system works for the proposed model at levels 4, 5, 6, and 7. The error can be referred to the different resolutions of F/T sensor and the encoder (Error in stiffness between theoretical and experimental: L4:3% L5: 8.3%, L6: 6.8%, L7: 8.3%) .
V. HAPTIC INTERFACES & THE PSYCHOPHYSICAL TEST

In order to measure the capability of the BpVSJ to display different levels of stiffness that are cognitively realized by users, two tasks as part of a psychophysical experiment were performed on volunteer participants. The experimental protocol is similar to [65]. The tasks were designed to be totally passive, where only active-push cognitive tasks were be performed: the Relative Cognitive Task and Absolute Cognitive Task [65]. In this section, the participants’ selection criteria, the experimental design and setup, detailed procedures, as well as the experimental results are detailed.

A. EXPERIMENTAL SETUP

Three mimic devices were fabricated, each consisting of an output link, and a torsional spring. The stiffness value of each spring is similar to one of the values rendered by BpVSJ (see Fig. 12). The springs were selected to approximately represent levels L1, L3 and L5 of the BpVSJ. The detailed design parameters of the springs are shown in Table VI. Hereinafter, the mimic device with the springs with highest stiffness, intermediate stiffness, low stiffness will be labeled as SH, SM and SL, respectively. The rendered levels in the BpVSJ (levels L1, L3 and L5) will be denoted as L, M, and H, respectively.

![Stiffness Mimic Devices with Calibrated Springs](image)

The tips of the output links of SH, SM, SL and the BpVSJ were covered with 1 mm plastic pads in order to minimize perception bias in terms of the material softness or temperature.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SH</th>
<th>SM</th>
<th>SL</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torsional Stiffness</td>
<td>2518.6</td>
<td>1513.0</td>
<td>496.5</td>
<td>N.mm/deg</td>
</tr>
<tr>
<td>Wire Diameter</td>
<td>8</td>
<td>7</td>
<td>5</td>
<td>mm</td>
</tr>
<tr>
<td>Outer Diameter</td>
<td>27</td>
<td>22</td>
<td>15</td>
<td>mm</td>
</tr>
<tr>
<td>Number of Active Coils</td>
<td>4.25</td>
<td>5.25</td>
<td>6.25</td>
<td>Coils</td>
</tr>
<tr>
<td>Material</td>
<td>Stainless Steel A316 Alloy</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

B. PARTICIPANTS

20 right-handed healthy participants (9 Females, 11 Males, Age: 30.5 ± 3.74) gave their informed consent to participate in the two task experiment. Exclusion criteria consisted of any upper-body physical limitations, disease or movement dysfunction that may affect the experimental outcomes. The experimental procedure was approved by the Ethics Committee of Healthpoint Hospital – Abu Dhabi – United Arab Emirates (Ref. REC006).

C. ACTIVE RELATIVE COGNITIVE TASK

During this task, the participants were guided to use the tip of their thumb to probe and sort three levels of stiffness as rendered by the BpVSJ. More specifically, the participants were presented with 5 different sets of stiffness. Each set included 3 stiffness levels randomly displayed that the participants were asked to rank from the lowest to the highest stiffness. During the experiment, the participants were seated on a chair, blind-folded and were exposed to an acoustic white-noise in order to prevent any auditory or optic cue. They were granted unlimited time to perform the task, and guided to push the stylus of the BpVSJ using the thumb of the dominant hand until the stylus deflected by 5-10 degrees. It’s worth to mention, that even BpVSJ is not following the linear behavior of stiffness level 5 when the deflection exceeds 2 degrees, the torque and stiffness is relatively higher than previous stiffness levels. Thus, the user will still feel higher stiffness. The results are shown in Table VII, where the perception of the stiffness displayed by the BpVSJ was associated with the perception of the real values in a confusion matrix. The diagonal of the matrix represents the right answers.

![Confusion Matrix of Relative Cognitive Task](image)

<table>
<thead>
<tr>
<th>Displayed</th>
<th>H</th>
<th>M</th>
<th>L</th>
<th>Relative Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>96</td>
<td></td>
<td></td>
<td>96</td>
</tr>
<tr>
<td>M</td>
<td>0</td>
<td>97</td>
<td>3</td>
<td>97</td>
</tr>
<tr>
<td>L</td>
<td>0</td>
<td>1</td>
<td>99</td>
<td>99</td>
</tr>
</tbody>
</table>

D. ACTIVE ABSOLUTE COGNITIVE TASK

In this task, participants were guided to use the tip of their thumb to probe three levels of stiffness as rendered by the BpVSJ and relate them to their physical counterparts displayed on the mimic devices. The participants were presented with the randomly displayed stiffness levels. Each of the three levels were randomly displayed 5 times. The participants needed to associate the rendered stiffness with its physical counterpart using their left hand. During this task, the participants were also seated on a chair, blind-folded and exposed to an acoustic white-noise in order to prevent any auditory or optic cue. They were granted unlimited time to perform their task and guided to push the stylus of the BpVSJ by the right thumb and the stylus of the mimic device by the left thumb, such as either styli would deflect 5-10 degrees (Fig. 13). The results are depicted in Table VIII, where the perception of the stiffness displayed by the BpVSJ was associated with the perception of the real...
values in the mimic devices in a confusion matrix. The diagonal of the matrix represents the right answers. The errors of the absolute cognitive tasks may be explained by the laterality of the participants and the fact that the mimic devices have less friction compared to BpVSJ as the mimic devices have no gears.

<table>
<thead>
<tr>
<th>Displayed</th>
<th>Real</th>
<th>SH</th>
<th>SM</th>
<th>SL</th>
<th>Relative Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>74</td>
<td>26</td>
<td>0</td>
<td>74</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>7</td>
<td>77</td>
<td>16</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>0</td>
<td>2</td>
<td>98</td>
<td>98</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE VII** CONFUSION MATRIX OF ABSOLUTE COGNITIVE TASK

**FIGURE 12:** Participant performing the Absolute Cognitive Task

### E. RESULTS DISCUSSION

Two psychophysical experiments were conducted with 20 healthy participants. These experiments are the Relative Cognitive Tasks (RCT) and the Absolute Cognitive Tasks (ACT). These experiments are well-established in literature [64, 65] to validate the capability of a haptic interface to render a physical stimuli (stiffness for this case) and being recognized by the users. In the RCT, the users will feel different levels of stiffness rendered by the haptic interface and they’re requested to order these levels from highest to lowest. While in ACT, the users will feel different levels of stiffness from the haptic interface and they are requested to match it with their calibrated counterparts on a mimic device.

The results of conducting such experiments are plugged in a confusion matrix, which relates the stiffness level recognized by the users to the actual stiffness value they felt. If the user recognized the actual stiffness level, it is considered a right answer. If the user confused the actual level of stiffness with another value then it is considered a wrong answer. The percentage of the right answers reflects the relative accuracy of recognizing this particular level of stiffness. The average of the relative accuracies reflects the capability of the haptic interface of rendering different levels of stiffness and verify it to be used by humans.

Comparing the results of BpVSJ with the validated haptic interfaces proposed in [64, 65], the results show that the users have recognized the levels of stiffness rendered by the BpVSJ with an average of 97% for the Relative Cognitive Task, and 83% for Absolute Cognitive Task. In [65], similar experiments were conducted on the validated haptic interface and the results of the Relative Cognitive Task is 91% and Absolute Cognitive Task is 82%. While in [64], only Relative Cognitive Task is conducted to validate the proposed device and the results are an average of 70%. From this, it can be concluded that BpVSJ is verified as haptic interfaces.

### VI. DISCUSSION

The design of BpVSJ goes under the category of Series-Parallel Elastic Actuators (SPEA). This designs proposed in this category were driven by the need to minimize energy consumption, peak torque, or power consumption in robots and humans [57].

In literature, several concepts of SPEAs were presented. The iSPEA [58] and the MACCEPA-Based SPEA [59] are two examples of SPEAs which benefit from an intermittent mechanism to recruit the parallel elastic elements in succession. While BpVSJ benefits from the gear train formation and the brakes to allow the freedom in selecting the level of stiffness without the need of succession involvement of elastic elements. Similar to BpVSJ, the work in [62] used electro-adhesive clutches to control the engagement of the elastic elements. The electro-adhesive clutches are well-known for their low power consumption, but the design in [62] still applies succession in elastic element involvement, which limits the freedom of selecting the level of stiffness at any desired position.

Although the current proof-of-concept is relatively large, the concept of the design allows the designer to realize more compact versions. The current bulkiness is referred to the fact that all the used parts were off-the-shelf. The problem can be avoided by selecting stronger brakes, which will omit the need of the torque reduction gear stages. Compared to the previous proposed designs, BpVSJ has relatively fast response time with relatively low power consumption.

Passive haptic interfaces that involves variable stiffness mechanisms are found in literature in [34, 56, 66]. BpVSJ is able to achieve zero stiffness level, enabling its application in teleoperation applications, while in [34] the device covers a large span of stiffness levels benefitting from the concept of Variable Lever Mechanism (VLM) but is not able to achieve zero stiffness. The design proposed in [34] is quite bulky and the system is not easily scalable to be embedded in a revolute joint, while the design of BpVSJ is scalable and can be embedded in a revolute joint enabling it to be integrated with multiple-degrees-of freedom haptic interfaces. The concept altering the stiffness in pDVSJ [56] and pDVSJ-II [66] relies on changing the active length of an elastic cord [56] or the number of involved springs-in-series [66]. This was achieved through activating the novel selective-locking mechanism (Cord Grounding Unit (CGU)) which limits the motion of the free cord creating a new active length [56] or involve the desired number of springs [66]. In these designs, a single level of stiffness requires two springs (one spring per direction) yielding 0.5n levels of stiffness for n springs. While in BpVSJ, there are 2^n levels of stiffness for n springs. On the same hand, the devices presented in [56, 66] is capable to
change the stiffness from lower-stiffness to higher stiffness due to the usage of CGUs, while in BpVSJ, the user is capable to change freely from lower levels to higher levels and versa.

VII. LIMITATIONS

As BpVSJ belongs to the category of passive haptic interfaces, it inherits the limitations of all passive haptic interfaces in their inability to generate a force that will change the direction of motion of the user’s hand. This fact prevents passive haptic interfaces to be used in several applications like bilateral teleoperation with obstacle avoidance through artificial force fields [67]. Moreover, the system lacks controllable energy dissipative elements (i.e. brakes), the system is incapable to control its damping coefficients preventing it from being used in haptic applications where motion redirecting is required (i.e. path following [68]).

BpVSJ is designed to fully simulate the interaction of elastic elements without sacrificing the natural passivity of its system. The designated applications where BpVSJ can be is limited to exploration where remote object stiffness rendering is required. An example of such applications can be found in [66] where the passive haptic interface (BpVSJ in this case) can be used as a master device to teleoperated a remote slave manipulator that explores and inspects different remote objects by pressing on them (performing palpation). The stiffness is rendered on the haptic interface based on the force gradient transmitted through the bilateral teleoperation system. In case the virtual/remote elastic object has a fixed value stiffness, only one level of stiffness in BpVSJ will be activated during the interaction. While in case the remote/virtual object has a nonlinear stiffness, the level of stiffness in BpVSJ may change higher or lower based on the change in the behavior of the object’s stiffness.

The BpVSJ is meant to be used in exploration application where the joint will be moving freely till there is an interaction with an elastic element. Its supposed to change the stiffness from zero stiffness to the designated level. In our approach the objective is to discretely change the level of stiffness which is obviously less smooth than altering the stiffness of an active haptic interface, but has advantages in terms of speed of stiffness variation, and minimizing energy consumption which is the main motivation for the design topology. Moving towards multiple-Degrees-of-freedom haptic interface that incorporates the concept BpVSJ is achievable. The stiffness of the end-effector will be dependent on both joints stiffnesses and joints position. It can be speculated that the system will be less smooth than an active haptic interface.

VIII. CONCLUSIONS AND FUTURE WORK

This paper presented the BpVSJ as a proof of concept of a novel passive revolute joint that is able to vary its stiffness by leveraging the recruitment of Serial-Parallel Elastic Elements. The novelty of the system lies in its design topology, where three torsional springs are mounted on three planet gears on one side. The planet gears are directly connected to a sun gear mounted on the main shaft. The other side of the each spring is mounted on a brake through two torque reduction gear trains. The joint has shown unlimited motion of the output arm at the transparency level (zero stiffness where all brakes are inactive), and seven different stiffness levels based on combinations of active stiffness bits. The BpVSJ has demonstrated the capability of altering the stiffness at any joint angular position, where the recruitment of a particular stiffness level can occur at a non-equilibrium point without additional power. The theoretical stiffness model was experimentally validated, demonstrating that the stiffness can be altered on the linear ranges of the torsional springs.

To test the capability of the BpVSJ as a functional passive haptic interface for stiffness rendering, a psychophysiological experimental test was conducted with volunteer participants. The participants conducted two tasks: a relative cognitive task and an absolute cognitive task. The results confirmed that the BpVSJ is capable of rendering stiffness with high relative accuracy.

The simplicity of the BpVSJ design facilitates relative compactness and scalability of future versions. For wearable haptic interface, the current proof-of-concept realization suffers from bulkiness. The authors recommend applying dog clutches or tooth clutches for high torque to size ratio. This would allow for a more compact system without compromising the designated torque rates. Torsional plate springs would also potentially contribute to a more compact design. BpVSJ suffers from the friction by the gear trains, in order to reduce the friction and maintain the passivity of the system, the authors suggest to change the gear trains with a pulley-driven system.

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REFERENCES


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