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# Synergistic control of a multi-segments vertebral column robot based on tensegrity for postural balance

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## ABSTRACT

We present a neuronal architecture to control a compliant robotic model of the human vertebral column for postural balance. The robotic structure is designed using the principle of tensegrity that ensures to be lightweight, auto-replicative with multi-degrees of freedom, flexible and also robust to perturbations. We model the central pattern generators of the spinal cords with a network of nonlinear Kuramoto oscillators coupled internally and externally to the structure and error-driven by a proportional derivative (PD) controller using an accelerometer for feedback. This coupling between the two controllers is original and we show it serves to generate controlled rhythmical patterns. We observe for certain coupling parameters some intervals of synchronization and of resonance of the neural units to the tensile structure to permit smooth control and balance. We show that the top-down PD control of the oscillators flexibly absorbs external shocks proportionally to the perturbation and converges to steady state behaviors. We discuss then about our neural architecture to model motor synergies for compliance control and also about tensegrity structures for soft robotics. The 3D printed model is provided as well as a movie at the address <https://sites.google.com/site/embodiedai/current-research/tensegrityrobots>.

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## KEYWORDS

Motor synergies; central pattern generators; tensegrity; vertebral column; postural balance; phase synchronization; soft robotics; feedback resonance; biological robotics

## 1. Introduction

Animal's musculoskeletal system is based on a complex network of muscles, bones, nerves, tissues, and soft bodies which are hard to replicate accurately in robots [1,2]. This dense architecture is however **well ordered** so that the control done in the nervous system can realize easily flexible sensorimotor coordination at a very low energy cost with the dynamical grouping of the muscles known as motor synergies [3–5]. Nonetheless, in order to exploit fully the body structure, the nervous system has to organize itself flexibly and complementarily [6–8]. For instance, the **well distribution** of stress and strain throughout the body warrants its ecological control so that when we are exposed to a violent shock, we can still stand or bend our knees or stiffen (or soften) our body and joints with a small amount of control, just as a building would absorb an earthquake wave and balance itself, or as a bridge would lean into the wind. In comparison, current robots are still difficult to design and to control in order to achieve robust postural balance under external perturbations and dynamic motion.

In this paper, we propose to take inspiration of both (1) the human musculoskeletal system of the dorsal spine

and (2) the neural architecture at the spinal cords level to realize a multi-degrees of freedom vertebral column robot [9–12] and its neural controller in order to cope with external perturbations. Our first contribution is on the one hand on the design of an original neural controller composed of a **proportional derivative (PD)** controller and nonlinear oscillators in order to generate controlled rhythmical patterns and convergence to steady state behaviors. Our second contribution is on the other hand on the design of a novel vertebral column robot constituted of connected auto-replicative tensegrity elements [13] mounted vertically as a multi-segment inverted pendulum with soft links. To our knowledge, this coupling between a PD controller and nonlinear oscillators to control synchronization as a minimization process was never presented before.

We model the central pattern generators (CPGs) of the spinal cords with a network of nonlinear Kuramoto oscillators coupled internally and externally to the structure and error-driven by a PD controller using an accelerometer for feedback. We suggest that our proposed neural controller, although simple, is similar to the role played by the neuromodulators in the spinal cord that modulate the

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111 gain of the sensory feedback on the alpha-motor neurons  
 activity to generate the desired synergy [14–16]; which  
 means selecting the most expected resonant modes rela-  
 tive to the perturbation. In line with [8,17], we consider  
 116 postural coordination modes as emergent phenomena  
 giving rise to non-linearity properties such as phase tran-  
 sition, multistability and hysteresis [18].

The paper is organized as follows. In **Section 2**, we  
 present first our motivation for the design of a tensile  
 structure. In **Section 3**, we describe then its assembling  
 121 with replicated 3D printed elements, its motors and sen-  
 sors used in order to replicate the tendon-driven mecha-  
 nism and control of the human upper-body. We present  
 the neural oscillators used to model the so-called **CPGs**  
 and the feedback-driven PD control used to model the  
 126 neuromodulators. Tested in passive and active condi-  
 tions, the multi-DOF tensile structure shows a large spec-  
 trum of behaviors from very soft dynamics capable to  
 generate rhythmical oscillations to very rigid static pos-  
 tures capable to handle its own weight in every posture.

131 In **Section 4**, we propose four experiments to dis-  
 play the capabilities of our framework. In the first setup,  
 we define the dynamics in open-loop control for vari-  
 ous modes of coordination by varying the phase and  
 the duration of a pulse-width modulation (PWM) con-  
 136 trol and by analyzing the resonant frequencies of the  
 system and its rhythmical patterns. In the second exper-  
 iment, we analyze the system statically from a postural  
 viewpoint and study its robustness in the upward posi-  
 tion. In the third experiment, we propose to exploit error  
 141 feedback for closed-loop control of the structure using  
**CPGs** [19]. Depending on the values of the internal and  
 external coupling parameters, we can synchronize non-  
 linear oscillators modeled with Kuramoto units to the  
 resonant modes of the structure and entrain it freely  
 146 to specific directions. These privileged modes of syn-  
 chrony represent the natural motor synergies that are  
 possible to generate and control in the multi-segmented  
 structure [20].

151 In the fourth experiment, we employ a top-down  
 mechanism, a PD controller, that controls the amplitude  
 level of the oscillators in order to absorb the external per-  
 turbations gradually on the vertebral structure so that it  
 can return back to its resting upward posture. Depending  
 on the strength of external perturbation, the controller  
 156 will set the oscillators to a certain regime producing big  
 oscillations till recovery in order to absorb the shock.  
 In reverse, for tiny perturbations, the controller will set  
 the oscillators to a different regime that can dampen the  
 perturbations.

161 We discuss then the interest of our mechanical design  
 and of our neural network for controlling soft robots as  
 well as the links to human motor synergies.

## 2. State of art and motivation 166

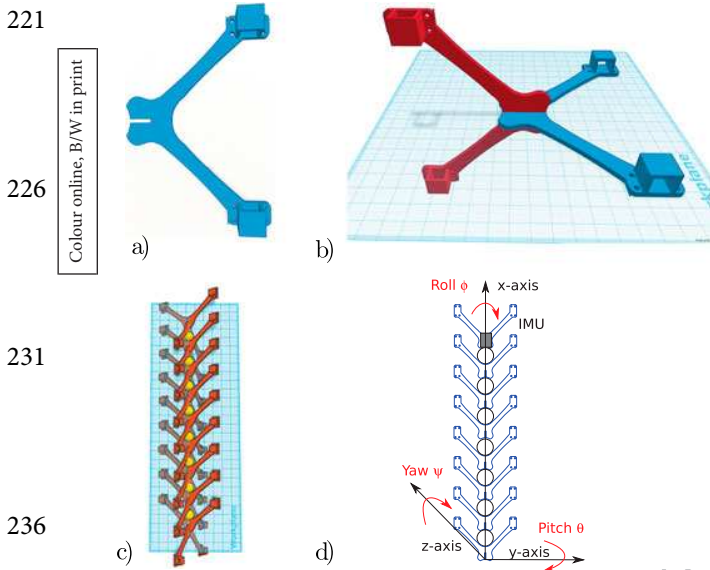
One architectural design that explains well biomechanical  
 compliance is tensegrity structures [21,22]. Tensegrity  
 structures can be seen as physical networks of stress and  
 loads so that they have an inner stress and plasticity in  
 171 their structure that make them resilient, adaptive and  
 robust to some external loads. In comparison to most  
 robotic designs, they do not follow Newton's law for rigid  
 bodies as they have no joints and no momentum or  
 torque since the motors are not on the axis of articulation.  
 176 Instead, they follow Hooke's law for elastic bodies. These  
 features make them a promising paradigm for integrat-  
 ing structure and control design [23–25]. For instance,  
 we can easily formalize a tensegrity system as a network  
 of tension (muscles and soft tissues) and compression  
 181 (bones), or as a network of springs and masses [26,27].  
 Therefore, they can be viewed as complex dynamical  
 systems with many degrees of freedom [10,28,29],  
 which is a property often seen in biological systems  
 [30–32].

The redundancy and nonlinearity within such dynamical  
 system might be considered at first as an obstacle to control,  
 however, the symmetries of the overall structure and the  
 many resonant modes generated can serve to decrease the  
 dimensionality of the control problem. For instance, one  
 way to have an adaptive control is to exploit phase synchro-  
 nization of these modes **similar** to coupled chaotic maps  
 [7,33].

In human control, this work is achieved by the **CPGs**  
 at the spinal cord level, which are primitives that control  
 the muscle grouping for general motion behaviors [14,34].  
 When we are standing upward, for instance, groups of  
 muscles are dynamically selected to contribute to our sta-  
 bility depending on the error perturbation level and the  
 force direction [35,36]. In robotics, such bio-inspired  
 control is still difficult to model when we design a com-  
 pliant body with many degrees of freedom and non-linear-  
 ities. In previous works, we have shown how we can control  
 such high degrees-of-freedom system with chaotic control-  
 lers that *sync* dynamically to the resonant frequencies  
 of several robotic devices [29,37–39] and to human  
 partners [40]. We believe that this type of control conveys  
 some important features of the human musculo-skeletal  
 system control as done in the spinal cord by the **CPGs**  
 [34,41,42].

## 3. Material and methods 211

216 We present a tensegrity structure based on auto-replicative  
 elements, 3D printed and similar to the ones proposed  
 in [13,43], see Figure 1(a,b). This particular



**Figure 1.** Multi-joint vertebral column model based on auto-replicative tensile elements for soft robotics. (a–c) Each element forms a tetrahedron by its four edges, which ensures the whole compliance and tension distribution in the three directions when connected to other elements in line. (d) An Inertial Measurement Unit (IMU) is placed at the end of the structure for position control and acceleration feedback. We provide the design of the replicative element freely at the address [44].

motif reproduces the very stable structure of the tetrahedron (i.e. the pyramids) which can stand easily upward, see Figure 1(c,d). When two structures are assembled as two inverted pyramids, the coupled unit structure can move in two directions and can support small shear torsions as well in the third direction, which is ideal for modeling the human’s rotational joints.

In comparison to other types of tensegrity motives, this one has the advantage to require fewer structures and few junctions part. Each element is connected to others with springs, which confers to the design some visco-elastic properties comparable to pre-stressed structures. The tensile elements possess a stable configuration that returns even after applying some external force pressure (self-stabilisation). The whole structure has 10 elements connected with spherical joints (ping-pong balls), which models well the excentric rotations of bones articulation. The vertebral column measures around 1-meter height; and each element is occupying a volume of 11 centimeters cube. The system can be viewed as a three-dimensional version of mass-spring dampers mounted in series. The total weight of the robot vertebrae is under 800 g, counting the weight of the motors (25 g each) and of each element (30 g), which is very light concerning its size.

*Conception.* We display in Figure 2 the prototyping of the tensegrity model with motors inserted and springs attached. A better understanding of which part of the robot each motor actuates is provided further in the Muscle-Tendon section Figure 3. To show the properties of compliance and postural stability of the structure, we co-contract the motors and set its neutral postural configuration respectively in the horizontal plane and in upward tension, so that the structure has a maximum momentum and tension on its morphology horizontally and has to exploit its physics fully to stand vertically; see resp. Figure 2(a–c). The balanced forces distribution of each motor-driven cables on the whole structure makes it stabilized in every position, even for the less energetic ones as the horizontal plane or the vertical plane, which are also difficult for humans who develop different strategies to support their own postural balance [18, 31,36,45].

*Sensory acquisition.* To perceive the motion, an inertial measurement unit (IMU) is placed at the top of the vertebral column as shown in Figure 1(d). This module possesses one accelerometer and a gyroscope, which permits to measure an angular velocity in rad/s and linear acceleration in rad/s<sup>2</sup>. Since the Gyro drifts slowly from its position and the accelerometer has high-frequency parasites, we can combine the two information to get rid of the slow variations of the gyroscope (high-pass filter) and the fast variations of the accelerometer (low-pass filter). The equation of the complementary filter for the  $\angle Y$  angle is:  $\theta_{IMU} = 0.98x(\theta + Gy/dt) + 0.02xY_{acc}$ . Where  $Y_{acc}$  is the angle of the accelerometer in degree and  $Gy$  the variation of the gyroscope. We mount the IMU at the extremity of the structure to have the maximum amplitude variation as the feedback signal. We plot in Figure 1(d) the  $\angle XY Z$  coordinate system in which the  $x$ -axis is opposite to the gravitational field and points upward so that the IMU is aligned along the longitudinal axis of the robot, the  $z$ -axis is perpendicular to gravity and lies in the horizontal plane of the robot body and the  $y$ -axis is aligned in accordance to both the  $x$ - and  $z$ -axis in order to form a right-hand three-axis coordinate system. The rotations in roll  $\phi$ , yaw  $\psi$ , and pitch  $\theta$  represent changes in orientation about the  $x$ ,  $z$  and  $y$ -axes respectively, see Figure 1(d).

*Muscle-tendon model.* The structure is actuated by six electrical micro-motors with a gear head and a shaft that reel up a 10 cm tendon-like wire and assembled in opposite sides, two by two, all over the structure and every two segments to have some flexibility (under-actuation).

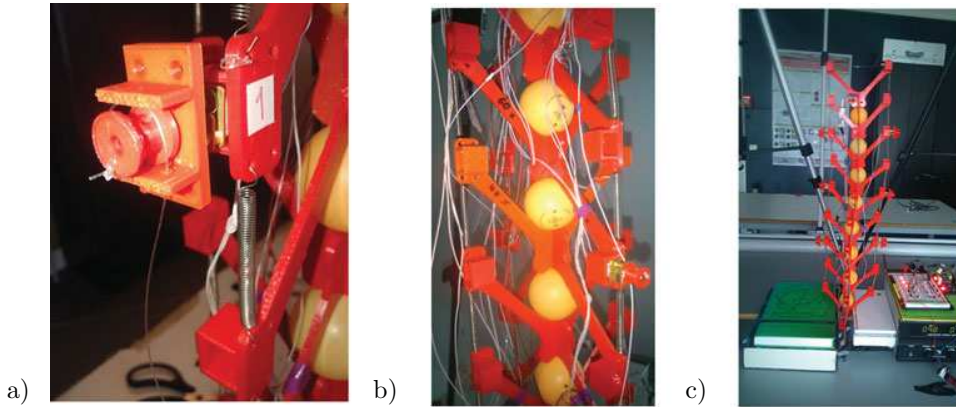
Using the same the nomenclature proposed by Geyer and Herr [46], we propose to model the system dynamics as actuated mass-spring-dampers connected in parallel and in series. For instance, each tensile element is

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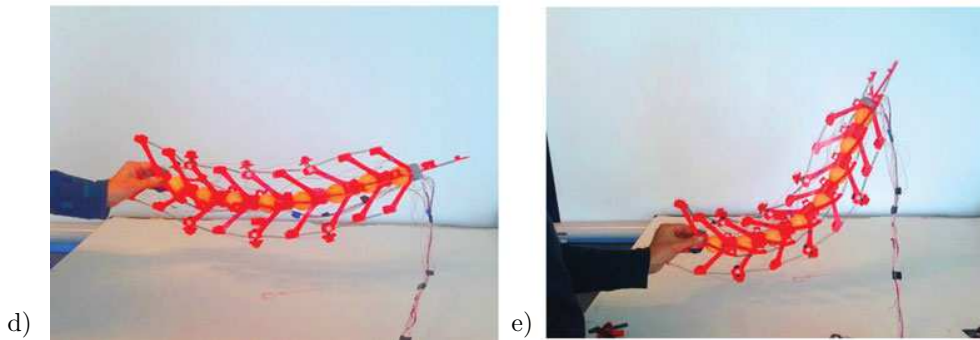
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**Figure 2.** Robustness in co-contraction in horizontal and upward postural configuration. Static postures demand to set the contraction of all the motors to specific lengths. In these situations, the motors act as rigid tendons and loads are distributed overall the structure. Maximal efforts are delivered on the structure when set at the horizontal in (a), in the vertical plane with different directions in (b), and upward at the vertical in (c).

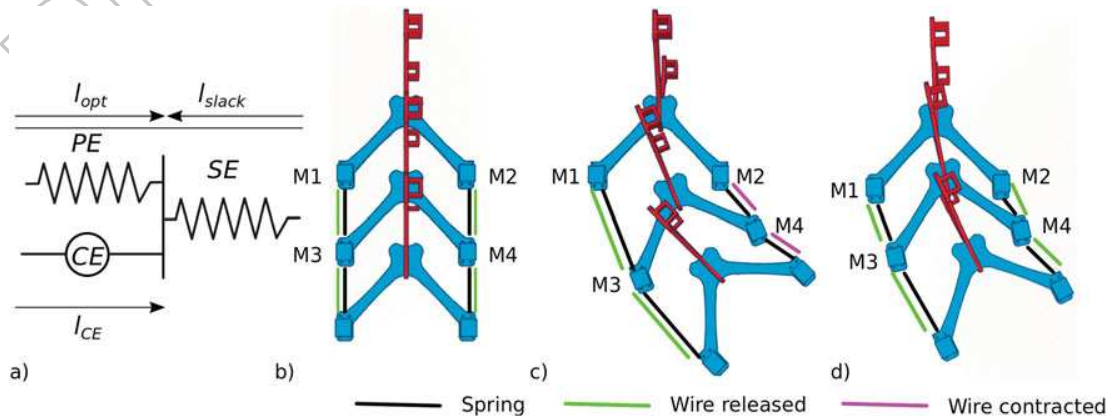
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**Figure 3.** Muscle model in co-contraction within the structure. Motors are mounted with springs in parallel and in series on the structure, which ensures the tensegrity system to be always pre-tensed. The motors pairs M1/M2 and M3/M4 are mounted in the opposite direction for co-contraction.

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431

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formed with an active contractive element (CE) together with elastic series (ES) springs constituting one muscle-tendon unit (MTU), see Figure 3(a). Each spring has an optimum length  $l_{opt}$  in which the global system is in a static configuration. if the CE stretches an ES spring beyond its optimum length ( $l_{ES} > l_{opt}$ ), a parallel

elasticity (PE) spring engages in the opposite direction so that its length becomes  $l_{PE} < l_{opt}$ . Conversely, as each tensile unit possesses two actuators mounted in opposition, the opposite PE prevents the ES of abrupt slack. We can now put in equation the system's behavior using these elements depending on the action of CE. Knowing

436

441 the stimulation  $S(t)$  of the muscle  $m$  and the muscle  
 time delay ( $\Delta t$ ) and gain  $G$ , we have  $S(t) = S_0 + G(l_{CE} -$   
 $l_{off})(t - \Delta t)$  where  $l_{off}$  is a length offset and  $S_0$  a stimu-  
 lation offset.

446 **3.1. Controllers**

We describe in this section the three different con-  
 trollers used to explain our original model to control the  
 soft vertebral robot. In the first section, we present the  
 error-driven PD controller and how it is implemented to  
 451 control the structure as a classical invert-pendulum.  
 In the second section, we present the oscillatory-based  
 Kuramoto network that creates the rhythmical synchro-  
 nization pattern in open-loop or in closed loop. And in  
 the third section, we present our original approach that  
 456 combines both approaches, PD+Kuramoto, for rhyth-  
 mical synchronization and error-based attenuation of  
 oscillations during external perturbation.

**PD control.** One common way to control the structure  
 in its upward position is to use PD controllers to mini-  
 461 mize the proportional (P) and derivative errors (D) based  
 on sensory feedback [46]. The variable ( $e$ ) represents the  
 tracking error, the difference between the desired input  
 value (R) and the actual output (Y), the angular position  
 computed from the IMU from the vertical axis.

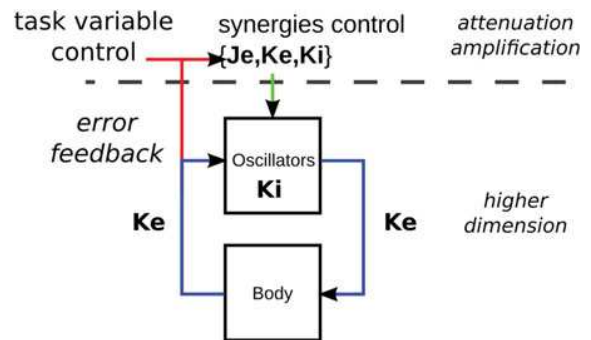
466 This error signal ( $e$ ) will be sent to the PD controller,  
 and the controller computes both the derivative of this  
 error signal. The signal ( $u$ ) just past the controller is now  
 equal to the proportional gain ( $K_P$ ) times the magni-  
 tude of the error plus the derivative gain ( $K_D$ ) times the  
 471 derivative of the error:  $u = K_P e + K_D \dot{e}$ .

This signal ( $u$ ) will be sent to the motors fed as a PWM  
 controller, and the new output ( $Y$ ) will be obtained.  
 This new output ( $Y$ ) will be sent back to the sensor  
 476 again to find the new error signal ( $e$ ). By convention, the  
 motor units on the left side will receive the command ( $u$ )  
 whereas the motors on the right side will receive the com-  
 mand ( $-u$ ). In the following experiments in Section 4, we  
 will control the tensegrity column in one plane only in  
 the  $Y$ -axis using a PD controller on the motor units or  
 the oscillators respectively in Sections 4.3 and 4.5.

481 **Kuramoto oscillators.** The PD control presented in the  
 previous section is driven by error feedback and can serve  
 as an adaptive strategy for stabilization if the proper coef-  
 ficients are found. In comparison, oscillator-based con-  
 486 trollers can model rhythmical patterns that can improve  
 the control of speed as well as robustness against noise  
 when the proper feedback-driven coupling is found. We  
 propose to model also this second type of controllers for  
 the balance and postural control of the tensegrity column.  
 491 We will use for that limit-cycle nonlinear oscillators,  
 which are employed in many robotic experiments to  
 model the spinal cord's CPGs [42,47,48].

The archetypal limit-cycle oscillators are the van der  
 496 Pol or Fitzhugh-Nagumo; however, we adopt in our  
 experiments the adaptive Kuramoto oscillator for its sim-  
 plicity to control the motor units. Each oscillator has its  
 intrinsic frequency and can receive interoceptive signals  
 501 either from other oscillators or descending controllers  
 and exteroceptive signals (in our case from the IMU  
 sensor), see Figure 4 the blue lines. Depending on the  
 504 coupling parameters for internal and external feedback,  
 the oscillators can have a phasic adaptation to the robot  
 motion, which can serve to accelerate it or to damper  
 506 it concerning the oscillator's own pace, or an abrupt  
 change to a non-rhythmic behavior.

Each oscillator  $\vartheta$  has its own intrinsic frequency  $\omega$ ,  
 and each one receives a linear combination from internal  
 and external dynamics. The internal coupling is done by  
 511 computing the phase difference between the oscillators.  
 The external coupling is done similarly by computing  
 the phase difference between the sensory feedback from  
 the IMU unit,  $\theta_{IMU}$  and the current phase of the oscilla-  
 516 tor  $\vartheta_i$ . We define the three coupling coefficients, **KI**, **KE**  
 and **JE** corresponding, respectively, to the internal cou-  
 pling among the oscillators, the external coupling of the  
 external signal to the units and the amplitude level of  
 the output signal to the motors. The internal coupling **KI**  
 521 synchronizes the oscillators from each other and reduces  
 their variability. The external coupling **KE** influences the  
 coupling to external perturbations. Besides, the control of  
 the amplitude signal to the motors **JE** is used to perturb



**Figure 4.** Hierarchical control based on top-down PD controllers  
 and bottom-up oscillators. The whole control of the motor syn-  
 531 ergies is based on the coupling parameters set {**KE**, **KI**, **JE**}. The  
 Kuramoto oscillators are coupled internally to each other based  
 on the parameter **KI**. The external coupling is done by the param-  
 541 eter **KE**, which sets the influence of the IMU sensor on the inter-  
 nal dynamics. The parameter **JE** acts on the amplitude of the  
 Kuramoto units. The rhythmical patterns produced by the oscilla-  
 546 tors can be controlled by a higher center of decision that selects  
 the global parameters for a desired postural control. This hierar-  
 chical control corresponds to a dimensionality reduction of the  
 controller on the robot dynamics to generate a feedback-based  
 closed loop control on oscillatory movements.

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551 and entrain the column. That is, the variable  $\mathbf{JE}$  changes  
the amplitude level of  $\sin(\vartheta_i)$  on the motor  $u_i$  and by  
doing so modulates the strength of the synchronization  
556 level between the oscillators and the multi-articulated  
structure. The variable  $\mathbf{JE}$  affects then the generated resonant  
modes observed at the body level. Furthermore,  
in order to take into account the symmetry of the structure,  
the intrinsic frequency of each co-contracting pair  
 $\{i, j\}$  are phase-shifted by  $\pi$  so that we have three units  
controlling the motor activity of six motors:  $\vartheta_i = \vartheta_j + \pi$ .  
561 We make the note that this effect is not shown in the  
equations.

$$\frac{d\vartheta_i}{dt} = \omega_i + \mathbf{KE} \sin(\theta_{\text{IMU}} - \vartheta_i) + \frac{\mathbf{KI}}{N} \sum_{j=1}^N \sin(\vartheta_j - \vartheta_i), \quad (1)$$

$$u_i = \mathbf{JE} \sin(\vartheta_i). \quad (2)$$

571 *PD control on the Kuramoto oscillators.* The parameters  
 $\{\mathbf{KI}, \mathbf{KE}, \mathbf{JE}\}$  set the oscillators to certain rhythmical  
regimes, which can be viewed as imposed motor synergies  
[5]. Therefore, one way to combine the **rhythmically based**  
control with the reflexive-based control presented  
before is to put atop of the oscillators a PD controller to  
576 modulate the values of the parameters set  $\{\mathbf{KI}, \mathbf{KE}, \mathbf{JE}\}$ .  
In comparison, the PD controllers atop of the Kuramoto  
network can modulate its parameters to tune the motor  
synergies or to repel them from discrete patterns. Therefore,  
the control of this parameter set  $\{\mathbf{KI}, \mathbf{KE}, \mathbf{JE}\}$  may be  
581 seen similar to the descending neuromodulators in the  
spinal cord that control the activity level of the alpha-  
motor neurons.

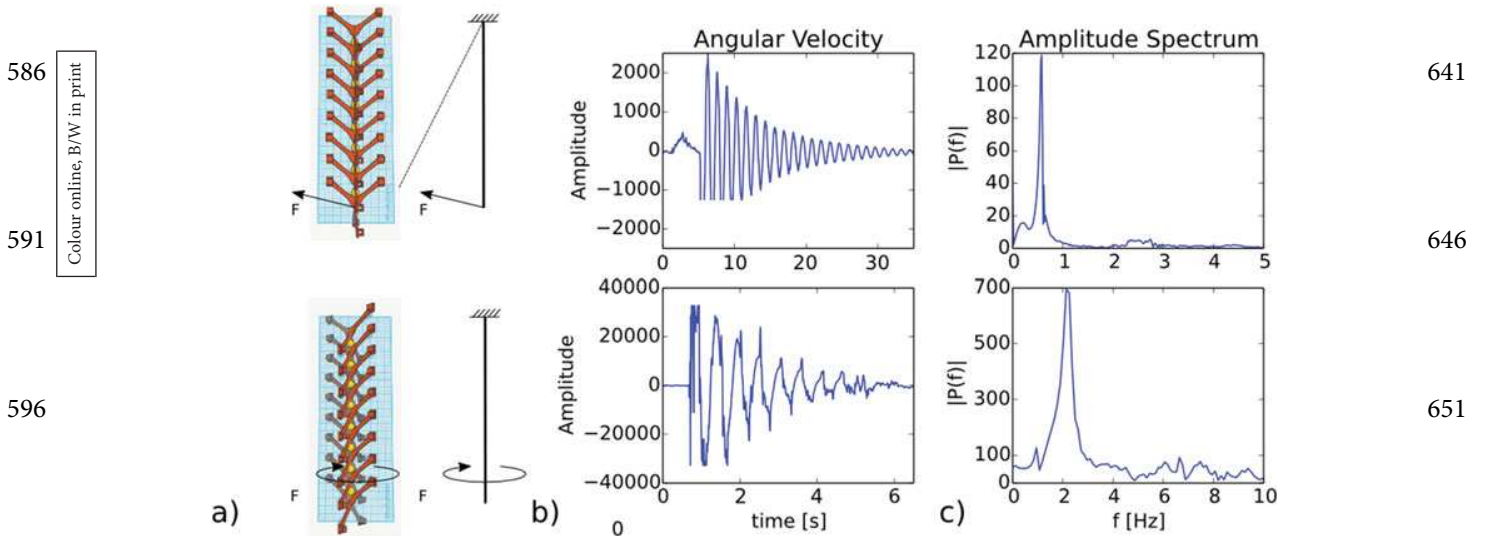
This compound controller will drive directly the oscillators  
606 toward desired regimes by changing the coupling  
parameters based on error feedback; the new circuit is  
plotted in red links in Figure 4. We use for that the distance  
93 to the vertical  $Y_{\text{err}}$  as a measure of the error  $e$  to  
611 synchronize the oscillators to the amplitude level of the  
perturbing force by updating the parameter  $\mathbf{JE}$  with the  
PD equations such that  $\mathbf{JE} = K_P Y_{\text{err}} + K_D \dot{Y}_{\text{err}}$ . Such a  
strategy may be similar to the task-level commands performed  
by the neuromodulators in the higher centers of decisions  
616 to bypass or to activate the synergistic control at the  
spinal cord level [4,5,15,35].

## 4. Results

We present in this section the results that characterize  
621 our soft robot with perturbations in passive mode in  
order to retrieve back its fundamental resonant frequencies  
94 (Sections 4.1 and 4.2) and in active mode to control the  
multi-segments structure for balance and standing upward  
based on error feedback and oscillations nearby its intrinsic  
626 frequencies (Sections 4.3, 4.4 and 4.5).

### 4.1. Dynamic behavior analysis in passive conditions

We make first a perturbation analysis of the whole structure  
and present its dynamic behavior when pushed in the frontal  
plane and when pushed on the transverse plane, respectively  
(Figure 5(a,b)). Specifically, we are interested in the passive  
636 response under external stresses and the response of the  
controllers.



601 **Figure 5.** Perturbation analysis on the vertical and axial plans of rotation, resp. top chart and bottom chart in (a) and (b). The Fourier  
transforms in (c) show the resonant frequencies of the structure. Two different fundamental resonant frequencies are found for the two  
656 axis, respectively 0.5Hz and 2Hz.

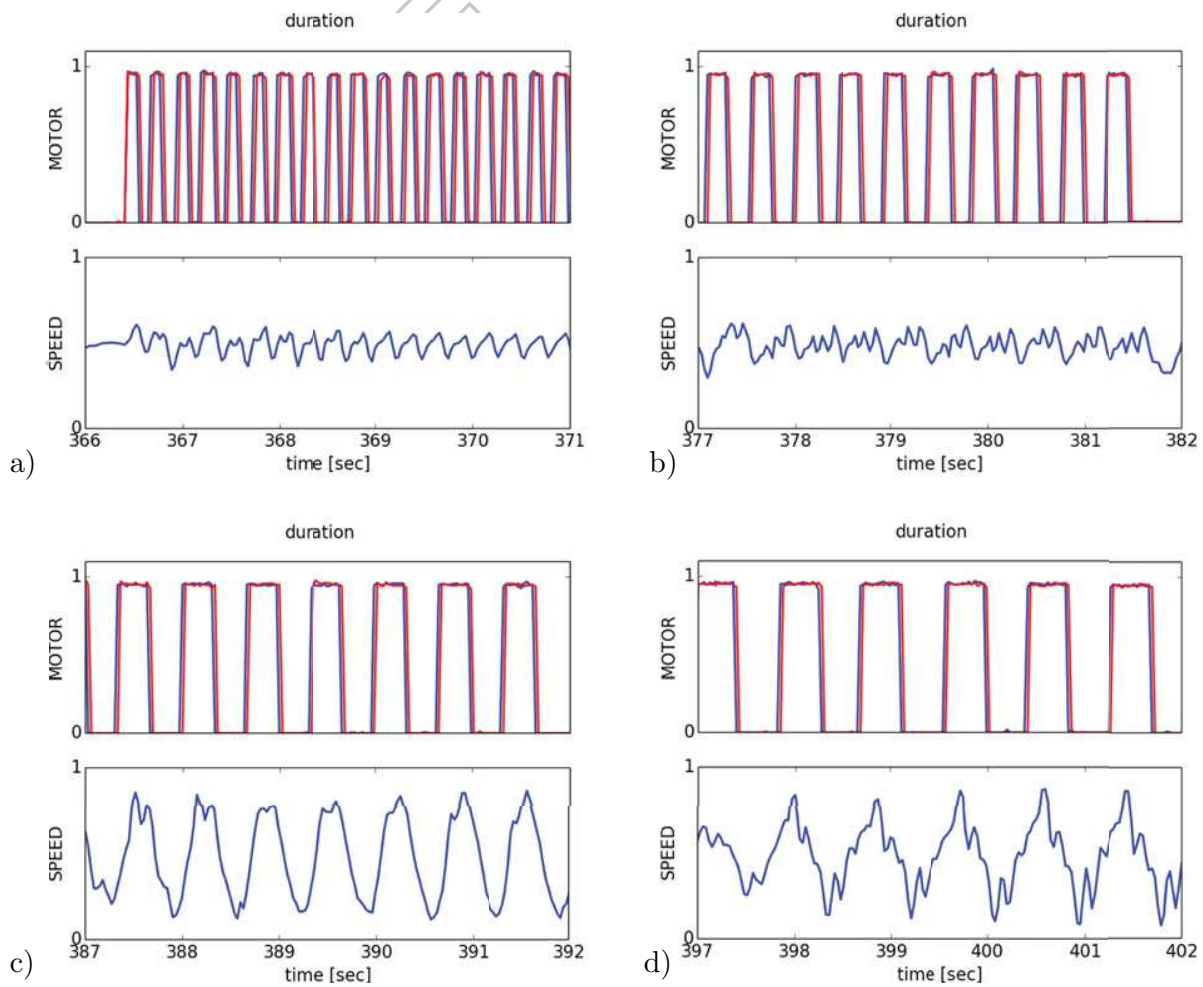
661 We display the Fourier diagrams for the two types of  
 perturbations. In Figure 5(a), the horizontal perturbation  
 on the structure produces a pseudo-periodic oscillation  
 with a fundamental mode around 0.5 Hz, whereas in  
 666 Figure 5(b) a perturbation around its axis of rotation gen-  
 erates an oscillation around 2 Hz. The structure can store  
 and release energy, which is important to develop resonant  
 modes and the motor synergies. The more elements  
 are linked together in the structure; the more resonant  
 modes can be generated.

671 As the structure is light with spherical joints, it has  
 few frictions except at its fixation point and behaves  
 like a pendulum. The number of oscillations till stabili-  
 zation is very large and above 10 oscillations for 30  
 seconds momentum for perturbations in the horizon-  
 676 tal direction, see Figure 5(b). Therefore, it is reason-  
 able to tune the intrinsic frequencies  $\omega$  of the oscilla-  
 tors nearby the ones of the structure to ease its motion  
 coordination.

716 **4.2. Resonant mode analysis in controlled conditions**

We propose to study in this section the control of the dif-  
 ferent resonant modes and phase delays of the structure  
 with open-loop controllers using PWM controllers. To  
 721 facilitate the analysis, we group the motors aligned sym-  
 metrically in the longitudinal plane forming two clusters  
 of three motors each. We control the phase delay and  
 duration of the PWM between the two motor groups  
 around the fundamental frequency.

726 If we modulate the duration of the PWM controllers  
 for all the motors as in Figure 6(a-d), respectively, from  
 50, 100, 250 and 500 ms, we can observe sensitivity on  
 the oscillatory patterns of the tensegrity structure. As  
 we might expect, large PWM produces large amplitude  
 731 oscillations whereas small periods of the PWM gener-  
 ate weak perturbations. The resonant mode occurs for  
 250 ms period square signal with amplitude variation 3  
 times larger than for PWM of 50 ms. Above this value,



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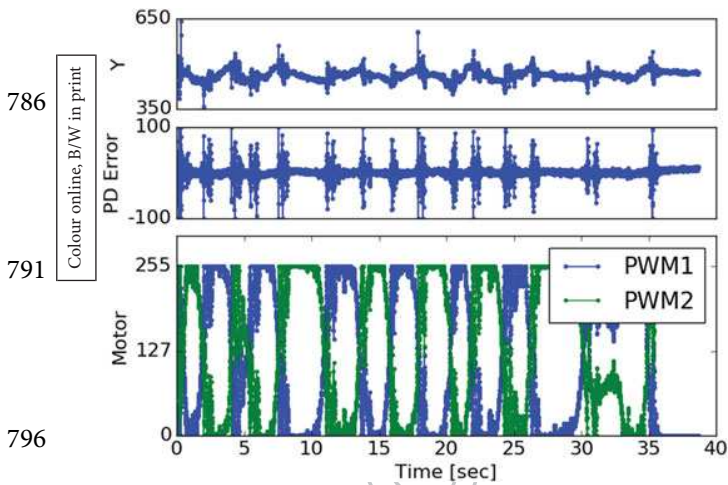
711 **Figure 6.** Phase duration characterization in controlled condition with PWM. A PWM signal controls the tensegrity structure in the vertical axis with motors aligned along the vertical axis. Modulating the phase duration of the motors, from small durations 50 ms (resp (a), 100 ms (resp (b), 250 ms (resp (c) up to 500 ms (resp. (d), affects the level of global synchrony and the apparition of complex modes of resonance. 766



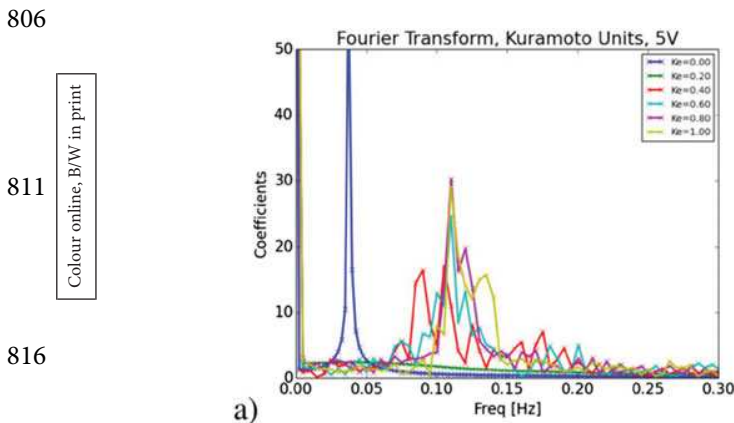
771 in the case of Figure 6(d), new harmonic modes are  
 772 super-imposed on the speed signal, which corresponds to  
 773 complex modes of coordination with the apparition also  
 774 of harmonic waves.

### 776 4.3. PD control

We perform first the error-based PD control of the  
 777 upward structure relative to the  $Y$  axis with directly  
 778  $e = Y_{\text{err}}$ , the relative displacement. The PD controller  
 779 can be written as  $u = K_P Y_{\text{err}} + K_D \dot{Y}_{\text{err}}$ . We present a



780 **Figure 7.** PD control with respect to external perturbations. The top  
 781 chart presents the displacement of the structure on the  $Y$  axis, the  
 782 middle chart displays the PD error and the bottom chart corresponds  
 783 to the motor output taken from two units in opposite side. The  
 784 perturbations are represented as strong deviations of the PD error  
 785 in the middle chart. In this graph, we show that the PD control  
 786 is capable of stabilizing the  $Y$  axis with a short recovery period  
 787 with respect to external perturbations.



806 **Figure 8.** Influence of the external coupling parameter  $KE$  on the resonant modes of the tensegrity structure. In (a), we plot the Fourier  
 807 coefficients with respect to the quantity of feeded back signal injected into the oscillators within the interval range  $KE \in [0.0, 1.0]$  from  
 808 open-loop control to stable closed-loop entrainment. In (b), we plot the details of the dynamics of one oscillator with respect to  $KE$  in the  
 809 interval range  $[0.15, 0.40]$  when the system bifurcates from an under-damped state to a rhythmical regime with the resonant frequencies  
 810 of the tensile structure.

826 graph in Figure 7 showing the structure  $Y$  displacement  
 827 to the vertical axis, the PD error computed and the motor  
 828 control on it. It shows that the PD controller rapidly  
 829 stabilizes its dynamics to the upward posture concern-  
 830 ing perturbations, which corresponds more to a reflexive  
 831 bang-bang controller when the  $K_D$  coefficient is tuned  
 832 with a small value relative to  $K_P$ . Although the structure  
 833 presents a rhythmical pattern, the transitions are abrupt  
 834 as we do not observe any resonant modes in this con-  
 835 figuration (top chart). In this control mode, the motors  
 836 contribute mostly to shock absorptions, which is less  
 837 energy-efficient and less compliant. We will study and  
 838 compare thereafter other controllers based on oscilla-  
 839 tors to overcome this problem of smooth control.

### 841 4.4. Kuramoto oscillators control

842 Our first experiment with the Kuramoto oscillators con-  
 843 sists in studying the interval range of the external cou-  
 844 pling parameter  $KE$  and see the impact feedback on  
 845 the internal dynamics of the oscillators when they are  
 846 coupled to it. We study first the Fourier coefficients of  
 847 Kuramoto's units when the control is done in a closed-  
 848 loop manner when we make to vary  $KE$  within the inter-  
 849 val range  $[0; 1]$ ; the motor signal is normalized within  
 850 the interval range  $[0, 255]$  and translated into PWM to  
 851 the motors. We display the result of the Fourier trans-  
 852 form in Figure 8(a) and of the dynamics of one motor in  
 853 Figure 8(b) within the interval range  $KE \in [0.15; 0.41]$ .  
 854 In our experiments, the internal coupling,  $KI = 0$  and  
 855 the amplitude level of the oscillators,  $JE = 1$  are not  
 856 changed.

857 When  $KE = 0.0$ , the oscillators drive the tensegrity  
 858 structure in a completely open-loop fashion to the

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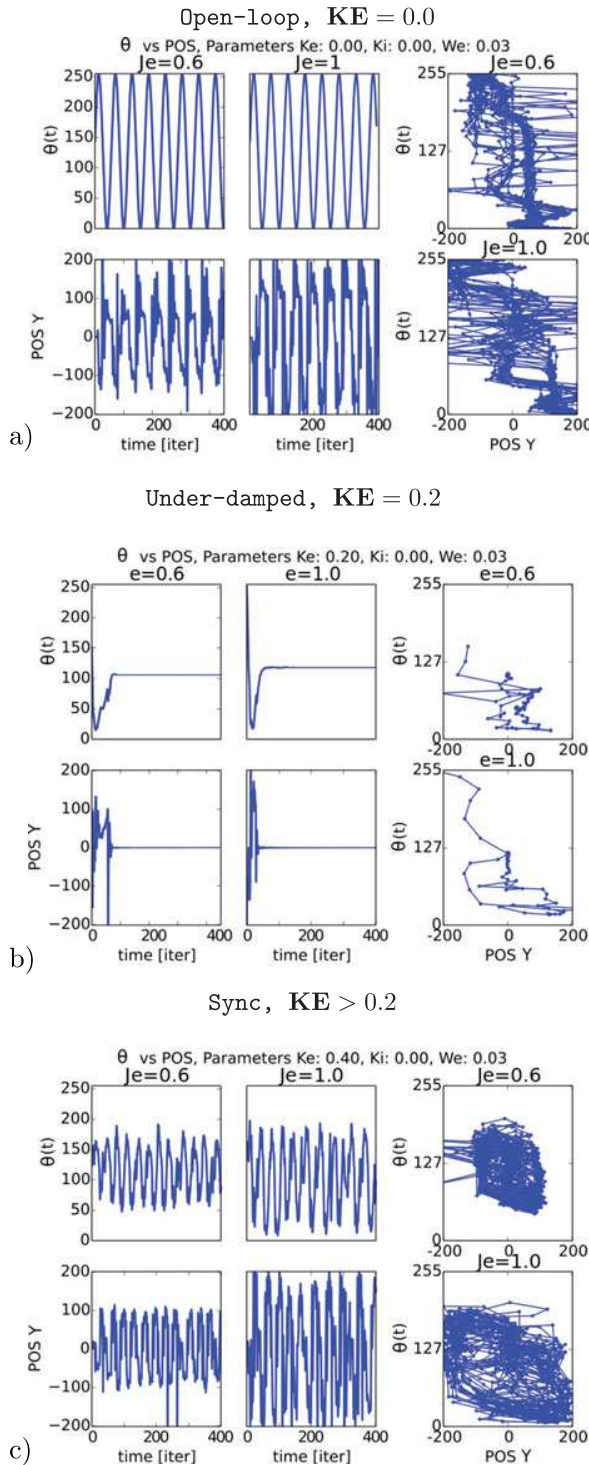
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**Figure 9.** Phase plots for external coupling  $KE$  corresponding to three different behavioral patterns and for different amplitudes  $JE$ . (a)  $KE = 0.0$ , the oscillators control in open-loop vertebral column to their intrinsic regime different from the one of the structure. (b)  $KE = 0.2$ , The oscillators go to a stable point attractor that return back when perturbed. This corresponds to a stable and passive pre-reflexive stage. (c)  $KE > 0.2$ , the general regime of synchronization is stabilized to generate rhythmical patterns around the center, which vary also depending on the motor force  $JE$ .

intrinsic frequency  $\omega$  of the oscillators. In this stage, the tensegrity structure performs a strong rhythmic motion. At  $KE = 0.2$ , an interesting behavior occurs in which the oscillators bifurcate to an attractor point, which is an under-damped postural configuration due to the friction of the ball joints. The friction poises the structure to the vertical position. The structure is slowly entrained by a slight feedback control till its immobilization. This posture is in this plot the upward posture with  $Y = 0$ . In this situation, the motors remain in this static posture without any feedback and react to small perturbations: when the structure is slightly pushed, the oscillators act reflexively to return back to the static posture.

Above this value, say for  $KE \geq 0.4$ , the oscillators start to be entrained actively by the external dynamics with a signal per noise ratio that depends on  $KE$  values. In this stage, the feeded back signal generates stable cyclic motion around the upward position in which, the higher the coupling coefficient, the higher the instabilities of the rhythmical pattern.

To understand in more details what is going on between the two regimes found, we plot the dynamics of the oscillator in the interval range  $KE \in [0.15; 0.4]$ , see Figure 8(b). In coherence with the results found in Figure 8(a), we observe a point transition only at  $KE = 0.25$ , which corresponds to a bifurcation diagram of the oscillators dynamics when they start to synchronize to the external dynamics of the body structure and start to mutually influence each other to this particular rhythm. This state corresponds to what is called feedback resonance, a mechanism that drives one system to its resonant frequencies by feedback and for certain coupling strength. This approach is similar to synergistic control [6,8], nonetheless, we characterized this phenomenon in robotics as a way to control postural coordination in different robotic systems [29,37–39].

We analyze in the next paragraph the three cases found depending on the coupling parameters  $\{KE, KI, JE\}$ .

We display three different phase plots for the three behaviors presented earlier with respect to  $KE \in \{0.0; 0.2; 0.4\}$ , see Figure 9 resp. (a–c). But to define more precisely the behavior of the system, we add two new conditions to compare with when  $JE = 0.6$  and when  $JE = 1.0$  that modulate more or less strongly each motor output. The two left columns of top charts indicate the oscillator's phase over time  $\vartheta(t)$  given to the motors between  $[0; +255]$  and the two left column of bottom charts indicate the vertical displacement over time  $Y(t)$  or  $Y_{err}$  relative to the vertical axis and normalized between  $[-100; +100]$ , which corresponds to  $[-30; +30\text{cm}]$ . The third column in Figure 9(a–c) corresponds to the phase plot of the two variables  $Y$  and  $\vartheta$ , respectively in the

991  $x$  and  $y$  axis, which describes the temporal dependence  
of the two variables. These graphs show the plots during  
1000 10s of the internal CPGs dynamics and of the position at  
the tip of the structure oscillating around the  $Y$  axis for  
 $\mathbf{JE} \in [0.6; 1.0]$ .

996 In Figure 9(a), the tensegrity structure is totally  
open-loop driven and forced to follow the oscillators  
cycle without any feedback. In contrast, the situation in  
Figure 9(b) corresponds to an under-damped case for  
1001  $\mathbf{KE} = 0.2$  where the oscillators go to a point attractor centered  
on the neutral position of the structure. Besides,  
when the coupling term  $\mathbf{KE}$  augments above 0.2 as it is  
the case in Figure 9(c), the Kuramoto oscillators start to  
be entrained to the phasic regime of the structure. In line  
1006 with the Fourier analysis in Figure 8, Figure 9 describes  
how the coefficient  $\mathbf{JE}$  affects synchronization and the  
system behavior as it is for  $\mathbf{KE}$ . We will present there-  
inafter in the next section the top-down control done  
on the global parameters  $\{\mathbf{KI}, \mathbf{KE}, \mathbf{JE}\}$  for updating the  
oscillators to the desired regime.

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#### 4.5. PD control on Kuramoto oscillators

The two methods presented in the previous Sections 4.3  
and 4.4 have different advantages regarding controllability  
1016 concerning the desired state (resp. the PD controller)  
and regarding compliance control concerning the desired  
rhythm (resp. the oscillators). The association of the two  
controllers type may permit to combine the advantages  
of the two worlds for generating one controlled entrain-  
ment to resonant modes and robust to perturbations. We  
propose to study this combined controller for the balance  
control of the tensegrity column in the upward posture by  
the amplitude modulation of  $\mathbf{JE}$  on the oscillators based  
on error feedback  $e$ . We remind the reader that  $\mathbf{JE}$  is gov-  
1026 erned by the equation  $\mathbf{JE} = K_P Y_{\text{err}} + K_D \dot{Y}_{\text{err}}$  where  $Y_{\text{err}}$   
is the horizontal displacement relative to the vertical axis.

We plot in Figure 10 four time series of the structure's  
stabilization for different pushes of gradual strength with  
the plot of the  $Y$  axis deviation in the top chart, and of the  
PD error over time in the middle chart and of the motor  
activity in the bottom chart for two motors in the oppo-  
1031 site side. In order to better understand the dynamics, a  
motion sequence is presented in Figure 11 of a recovery  
after a stroke and a movie are provided at the address  
1036 [https://sites.google.com/site/embodiedai/current-  
research/tensegrityrobots](https://sites.google.com/site/embodiedai/current-research/tensegrityrobots).

The top-down control strategy used to stabilize the  
structure is based on the modulation of  $\mathbf{JE}$  concerning  
the displacement on the  $Y$  axis employed as error feed-  
back. Depending on the perturbation force applied on  
1041 the structure  $\rightarrow$ , that we characterize in percent from

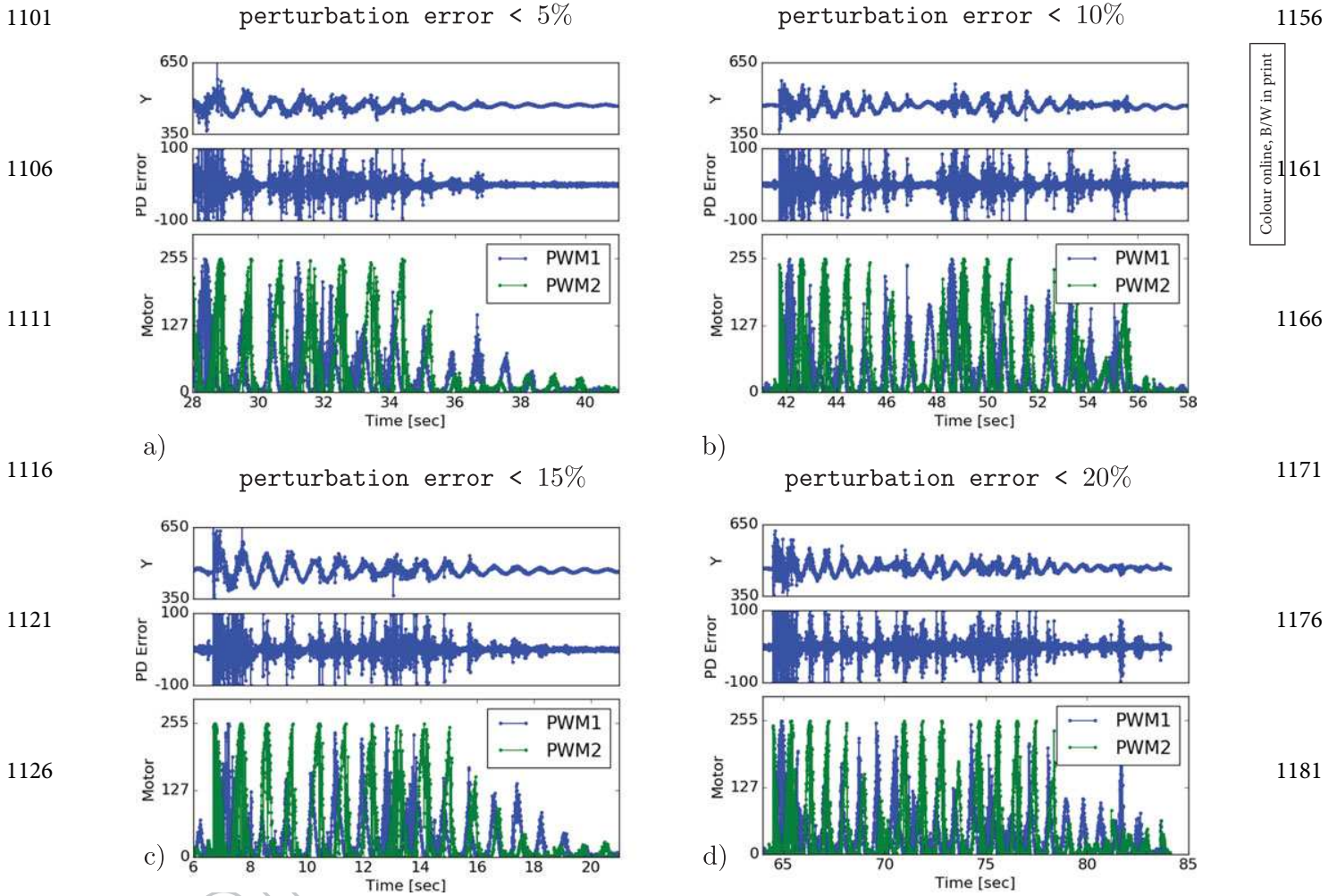
5% to 20% of relative displacement, various transi-  
1046 tory regimes can be observed till stabilization. This  
'resynchronization' process has an impact on the tempo-  
ral period, the phase and the frequency adaptation.

When a small stroke is applied as in Figure 10 (a,b),  
1051 the PD controller generates small amplitude variations  
till convergence of the oscillatory regime of the Kuramoto  
units with the damping of the structure between 10 and  
15s to its upward posture. The oscillatory regime of  
the CPGs is similar to an under-damped regime for a  
1056 spring-mass system with a long lasting transitory regime  
of a dizain of cycles. For instance, when the perturbation  
reaches 10% displacement, the PD controller desynchro-  
nize several times and takes several trials to re-stabilize  
the oscillators and the structure.

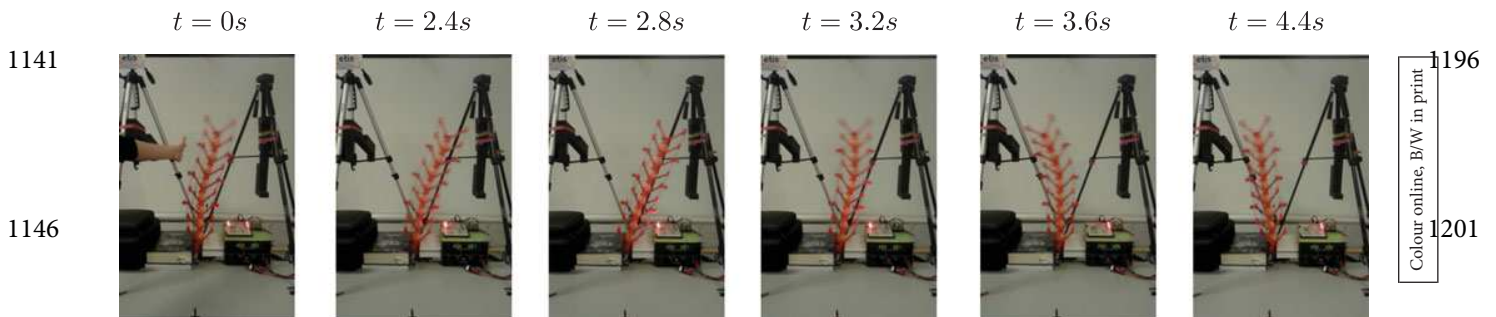
In the case of a strong perturbation as it is in Figure 10  
1061 (c,d) for 15% and 20% perturbations, the PD controller  
generates at reverse higher amplitude adaptations of the  
Kuramoto units till absorption of the shock and damp-  
ing of the structure. The temporal employed is slightly  
higher in this forced regime with a longer synchroniza-  
1066 tion stage diminution of the oscillators amplitude and  
phase difference. This behavior of the CPGs is similar to  
an over-damped regime for a spring-mass system with  
a faster transitory state of several seconds but after the  
stabilization of the oscillatory, which takes longer times  
1071 (around 20 cycles).

In all the situations, the oscillatory system finished  
with a small vibratory mode around the vertical axis due  
to the tuning of the PD coefficients, till its return back to  
a static posture with the release of the motors from co-  
1076 ntraction. Our strategy was efficient in all the studied  
cases, irrespective of the shock level but with some sen-  
sitivity of the PD controller to small perturbations due  
to its coefficients. These small perturbations made the  
system to slightly reactivate the oscillations as it is dis-  
1081 played in Figure 10(b) at time 48 s. We can understand  
from this figure that the external dynamics of the verte-  
bral column excites the oscillators and reactivates their  
dynamics.

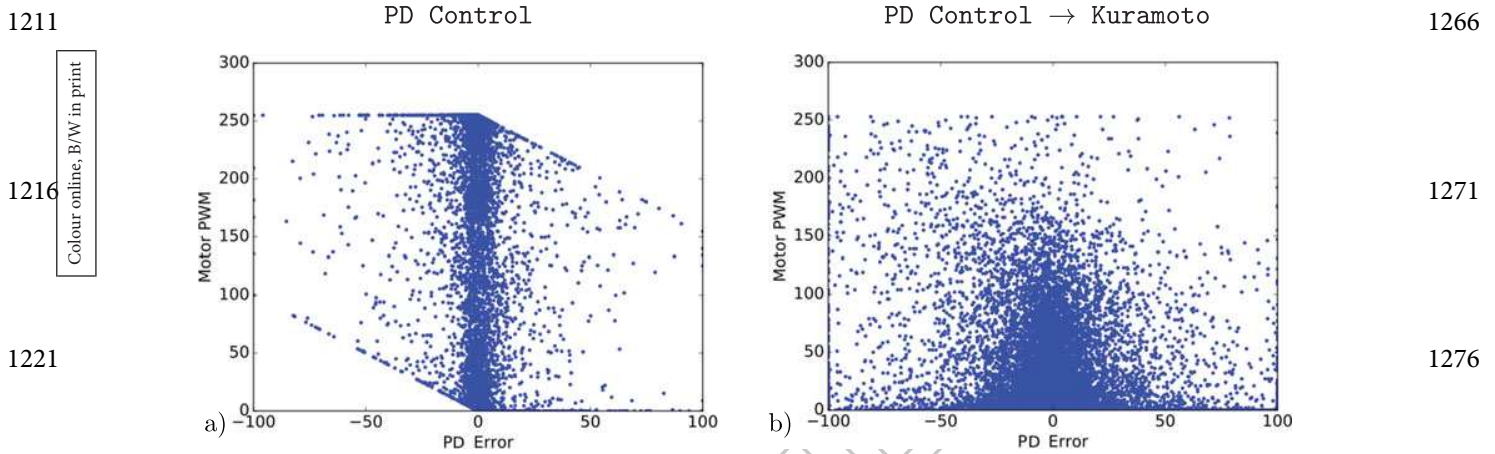
The top-down controller performed on the oscillators  
1086 permits to modulate more adaptively the strength of the  
motor synergies relative to the task than the PD con-  
troller. To compare the two strategies, we plot the error  
relative to the upward posture for the PD controller and  
the PD-controlled oscillators, respectively in Figure 12  
1091 (a,b). The figure shows that the second strategy (PD con-  
trol + Kuramoto oscillators) exploits more smoothly the  
motors with less strength applied on them (with a PWM  
below 150), which is at the price of a larger error vari-  
1096 ance. This complementary strategy exploits better the  
body structure and the motor synergies with unrestricted



**Figure 10.** Feedback control of the global parameter **JE** on the Kuramoto oscillators for various external perturbations. When a strong perturbation is imposed on the structure, an oscillatory regime is established by the top-down controller on the vertebral column to absorb the shock with a high amplitude till their attenuation. This transitory regime depends on the amplitude of the shock and of the velocity of the **JE** to steer the oscillators and the motors till their release when the column is stable enough to return back and stand at its upward posture. The more **JE** decays slowly, the longer the transition to a stable regime (under-damped oscillations). The more **JE** decays fastly, the quicker the transition to a stable regime (over-damped oscillations).



**Figure 11.** Motion sequence of postural balance after a stroke. A complete movie is provided at the address <https://sites.google.com/site/embodiedai/current-research/tensegrityrobots>.



**Figure 12.** Motor contribution with respect to the control strategy and perturbation. Comparison of motor dynamics between the PD controller in (a) and the PD controller on the Kuramoto oscillators in (b). In (a), the motors are strongly solicited to minimize error drastically from any perturbation. In (b), the motors are less strongly exploited; which has in consequence the loose error. The second strategy permits to exploit better the body structure and its passivity in order to have a more compliant and energy-efficient control on the body structure.

dynamics and loose error, which makes it better suited to absorb any external shocks.

## 5. Discussion

We presented a tensegrity-based model of a vertebral column robot controlled actively with nonlinear oscillators and feedback for rhythmical balance and upward posture. From a control viewpoint, the physics of this complex system requires to adopt a more bio-inspired type of control with loosely and parallelly distributed units for adaptation to the body dynamics [28]. In the end, the elastic properties of the tensegrity-based articulated trunk may ease its control [49]; i.e. its morphological control [50–52]. The **CPGs** in the spinal cord are local neural units that can generate a rhythmical pattern even without any feedback. Their activity, however, is always under the local feedback control of **muscle** spindle signals and the global feedback control of neuromodulators at the spinal circuits level or at the higher level. These feedback loops make these units embodied in the physics of the structure and contingent to a global coordination at the task level.

We use Kuramoto oscillators to entrain the vertebral column to its own rhythms and to synchronize them dynamically to the structure's resonant frequencies thanks to the IMU unit. This phenomenon is known as *feedback resonance* [29,37,53,54] and is used as a strategy to control the vertebral column to its resonant frequencies for shock absorption and postural balance. The tensile robot presents interesting damping properties that makes it easy to stabilize at the upward configuration, either passively or actively [55,56]. This is in line with

observations found on biological systems and humans on the importance of an actuated head and flexible trunk to body balance [18,31,45] and passive walkers [49,57]. We extended then the oscillator network to adaptive control with the use of feedback error for dynamical synchronization of the structure to the upward posture. This model is in line with other biological models of neurons for robotics that includes reciprocal, inhibitory and oscillatory modes [39,40,58,59]. However, our neural controller is combining PD control+oscillators in order to produce controlled rhythmical patterns, which is original and appears not used by other teams. Our feedback-driven oscillatory network controls global parameters for the dynamical entrainment of the resonant frequencies so that it can serve for discrete phase resetting [47] or modulated attenuation/amplification; this approach is in line with the proposal by Bizzi of motor synergies [34].

Our model presents also similar properties with [8,18] and provides realistic predictions of postural sway movements during erected head tracking. In our system, bifurcation and nonlinearities emerge from online optimization due to the combination of phase synchronized oscillators and PD control, which is difficult to achieve with offline models. Adaptation and recovery are possible only when synchronization is done around the frequencies of the body dynamics and found during the test phase. Further versions may examine the online discovery and learning of the structural parameters of the system and of the task, such as  $\omega$  and the coupling parameter  $\{KE, KI, JE\}$  and  $Y_{err}$ , by a top-down neural network or by a pseudo-inverse matrix that store and anticipate these information.

1321 We show that tensile structures present interesting  
properties for the design of soft and bio-inspired robots  
with the use of replicative elements to insure a redun-  
dancy of the global behavior at the macroscale level and  
flexibility with the many degrees of freedom of each ele-  
1326 ment. These structures are lightweights and pre-tensed,  
which make them physically robust to shocks even pas-  
sively as they distribute their tension on all their elements.  
Furthermore, their stiffness can be linearly controlled  
with the co-contraction of the motors to switch from a  
1331 flexible behavior to a rigid one. The dimensionality of  
the system makes it a complex system and the way to  
control it requires to exploit its passive dynamics and  
to entrain the controllers to its resonant frequencies for  
upward balance or rhythmical motion.

1336 Starting from this tensegrity-based vertebral column  
robot, it is natural then to think to design other body  
parts based on tensegrity [13,60]. We will attempt to  
go further in that direction with a more complex body  
and behaviors such as postural coordination and walking  
1341 [38]. At now, we have employed only one IMU unit in the  
top vertebral column to allow head-centered coordinated  
movements [18] as it is known that the vestibular system,  
perceiving rotational velocities and linear accelerations,  
uses this information to generate a unified inertial refer-  
1346 ence frame, centered in the head that allows whole-body  
coordinated movements and head-oriented locomotion  
[61,62]. In future works, we will employ more IMU units  
for each segment to have proprioception at the body level.

1351 Finally, as an educational tool, the scalability of tensegrity  
structures fulfills the requirements for testing ideas  
with low-cost and multi-disciplinary platforms at the  
community level for exploration and experimentation in  
robotics for Research, as well as in Art and Education.  
For instance, tensile structures can be 3D printed and can  
1356 be highly replicable, which can be interesting for the Do-  
It-Yourself community. In the complement of this paper,  
we provide a website of the project with links for down-  
loading freely the tensegrity modules for building it and  
to inspire and iterate on the project to one's own. Their  
1361 overall robustness and lightweight can be put forward in  
comparison to most robots, which are still fragile and  
expensive products to design and repair. The ecology of  
the body morphology changes also the way control in  
force and precision is done and requires to understand  
1366 biological control and to rethink it for robots.

## Acknowledgments

1371 We would like to dedicate this manuscript in memory of  
Stephane Garnier, our collaborator at ENSEA, who started to  
work with us on this project and passed away. We would like to  
thank Ihor Kuras for his help on this project.

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No potential conflict of interest was reported by the authors. Q5

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