PNAS RESEARCH ARTICLE | ENGINEERING

Bimodal buckling governs human fingers' luxation

Massimiliano Fraldi[a,b,1,2], Stefania Palumbo[a,b,1], Arsenio Cutolo[a,b,1], Angelo Rosario Carotenuto[a,b,1], and Davide Bigoni[c,1,2]

Edited by Huajian Gao, Nanyang Technological University, Singapore, Singapore; received July 9, 2023; accepted September 25, 2023

Equilibrium bifurcation in natural systems can sometimes be explained as a route to stress shielding for preventing failure. Although compressive buckling has been known for a long time, its less-intuitive tensile counterpart was only recently discovered and yet never identified in living structures or organisms. Through the analysis of an unprecedented all-in-one paradigm of elastic instability, it is theoretically and experimentally shown that coexistence of two curvatures in human finger joints is the result of an optimal design by nature that exploits both compressive and tensile buckling for inducing luxation in case of traumas, so realizing a unique mechanism for protecting tissues and preventing more severe damage under extreme loads. Our findings might pave the way to conceive complex architectured and bio-inspired materials, as well as next generation artificial joint prostheses and robotic arms for bio-engineering and healthcare applications.

finger joint | dislocation | tensile buckling | elastic stability

Bones are connected through joints, the articulations, permitting the specialized movements necessary for everyday activities and, simultaneously, providing stability to the musculoskeletal system.

Among the structurally and functionally different types of articulations, synovial joints—also known as diarthroses—offer the highest degree of motion and are typical of shoulders, knees, elbows, hips, hands, and feet (1, 2), which are all indeed implicated in locomotion and handling of objects (3).

In human fingers, the diarthroses house the terminals of the joined bones in a cavity enveloped by an articular capsule (4) that structurally connects the adjacent bones by way of its outermost fibrous layer and secretes a viscous fluid filling the space of the cavity through an inner membrane, the synovium, Fig. 1. Both the synovial fluid and the sheets of hyaline cartilage that coat bones' articulating surfaces eliminate friction and absorb shocks during movements (5–7). Finally, extracapsular ligaments (7, 8) and the suction-like effect, which provides negative intra-articular pressure in response to bone ends' distraction (i.e., separation) (9–14), contribute toward mechanical stabilization of the joint (15).

As a result of their continuous involvement in body movements, synovial joints are frequently subject to injuries, luxations being among the most common ones. They consist in an abnormal displacement between the articulating bones, whose ends in contact move out of their anatomical position, either for returning back (sub-luxation) or fully and irreversibly dislocating (complete luxation) (16–18). In fingers, dislocations typically occur in case of impacts due to falls or collisions during sport (19, 20), or as a consequence of over-stretching caused by climbing or accidental fingers' trapping (21–23).

From a mechanical standpoint, luxations can be seen as the response of the bone-joint-bone structural system to either abnormal compressive or tensile forces, giving rise to the two mechanisms sketched in Fig. 1 and highlighted by X-ray images as well. The geometrical configurations assumed by dislocated fingers, which recall deviation of hinged bars due to elastic stability, as well as the extremely regular shape of the bone epiphyses shown in Fig. 1, prompts the question of whether luxations may conceal a mechanical strategy to preserve bone integrity and minimize irreversible tissues damages, in the event of extraordinary loads.

To investigate this theoretically, and inspired from the two different curvatures exhibited by the bone ends at the joint level, a structural all-in-one paradigm is introduced in the present article, capable of undergoing both tensile and compressive buckling in two orthogonal planes, whose resulting kinematics retraces the corresponding two above-mentioned dislocations phenomena. To best mimic the real physiology of the finger's joint, the mechanical model is equipped with elastic elements simulating ligaments and the suction effect due to the synovial capsule is additionally incorporated.

Significance

Fingers' joints are structural units that connect different bone tracts, providing simultaneously mobility and mechanical stability. Due to accidental overloads, finger joints can undergo luxations, which lead the articulating bone heads to dislocate from their anatomical position. We interpret this phenomenon as a unified elastic buckling mechanism induced by both critical compressive and tensile loads and ruled by the characteristic complementary curvatures exhibited by the joint geometry in orthogonal anatomical planes. With the aid of a theoretical model and of an experimental proof-of-concept, we show how luxations represent a natural instability-based strategy to lower excessive mechanical stresses and avoid more severe injuries potentially compromising fingers' functionality.

Author affiliations: [a]Department of Structures for Engineering and Architecture, University of Napoli "Federico II", Napoli 80125, Italia; [b]Laboratory of Integrated Mechanics and Imaging for Testing and Simulation, University of Napoli "Federico II", Napoli 80125, Italia; and [c]Department of Civil, Environmental and Mechanical Engineering, University of Trento, Trento 38123, Italia

Author contributions: M.F. and D.B. designed research; S.P., A.C., and A.R.C. performed research; and M.F., S.P., A.C., A.R.C., and D.B. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

[1]M.F., S.P., A.C., A.R.C., and D.B. contributed equally to this work.

[2]To whom correspondence may be addressed. Email: fraldi@unina.it or davide.bigoni@unitn.it.

Published October 23, 2023.

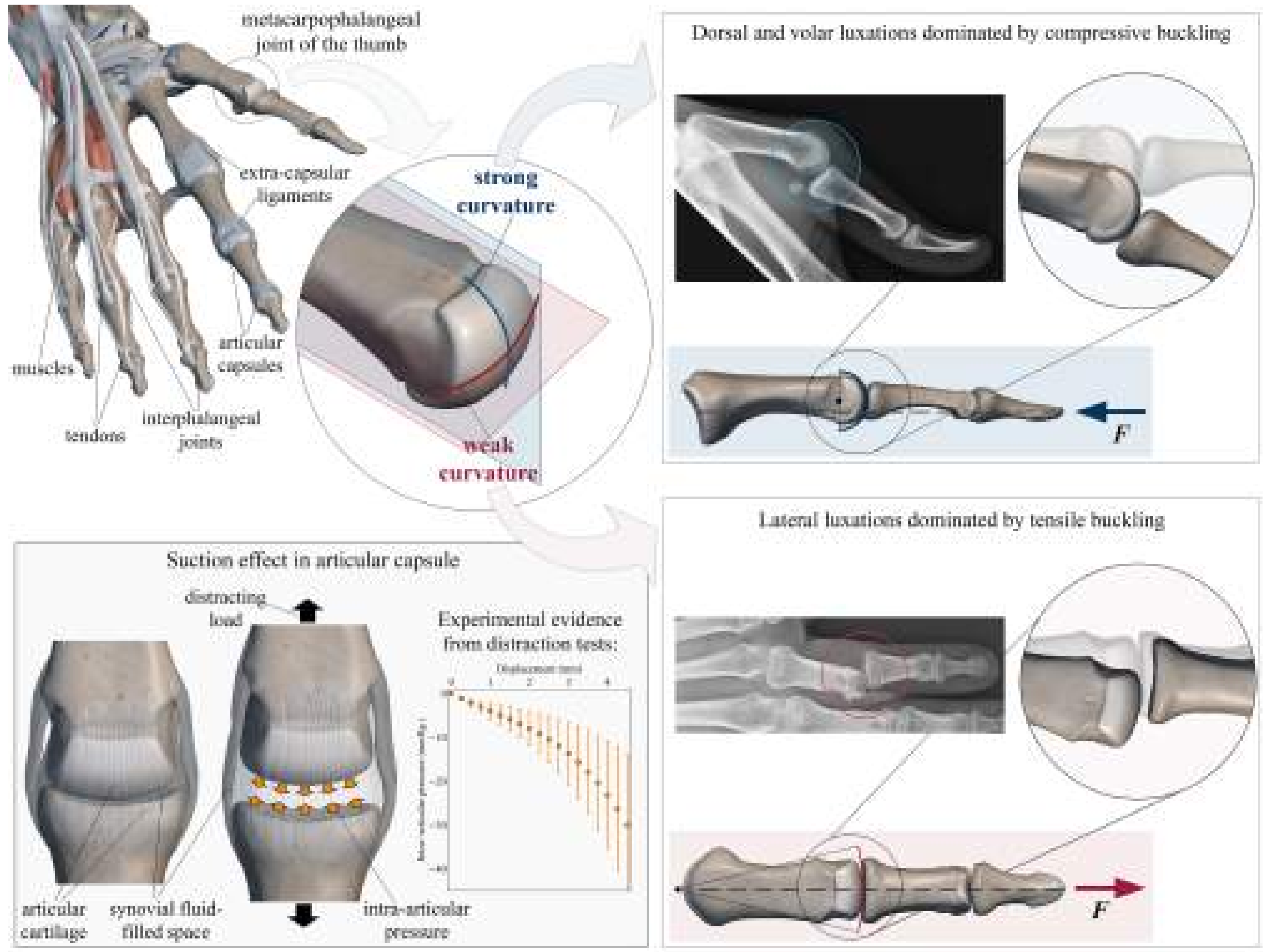

Fig. 1. On the *Left*, a sketch of the anatomy of the human hand highlighting the main components of the musculoskeletal system that drive the mechanics of finger joints, with a focus on the suction-like effect limiting articular distractions, inset adapted from ref. 9. On the *Right*, sketches and original RX images reproducing the complementary mechanisms of finger joints' dislocation occurring in orthogonal anatomical planes of the hand: example of compression-induced dorsal/volar luxation in the sagittal (or lateral) plane, characterized by a strong curvature of the bone terminals, and illustration of a lateral luxation determined by a high tensile load in the transversal (horizontal) plane, where a weak curvature marks the geometry of the bones' ends.

In this way, buckling-induced deviation of bone segments from their physiological configuration is demonstrated to allow a strong decrease of the overall elastic energy and a relief of mechanical stresses, so preventing cracking in bone and tears of ligaments and tendons, under both compressive and tensile accidental loads. Our conclusion is that the finger structure not only provides a key manifestation of tensile buckling in nature (24) but might also represent a unique biological system whose geometrical and mechanical features are optimally designed to shield tissues from high stresses, by harnessing in one system both compressive and tensile elastic instabilities (25–28). This could open interesting perspectives for integrated neuro-mechanical design of bionic hands, robotic prostheses, and exoskeletons for human rehabilitation and other bioengineering applications (29).

A Luxation-Inspired All-in-one Buckling Paradigm

The epiphyses of fingers' bones, at interphalangeal and metacarpophalangeal joints, evidence two remarkably different curvatures in the two orthogonal anatomical planes, which affect the type and range of movements of the articulated bone segments (Fig. 1). In fact, an ideal longitudinal section through the sagittal plane highlights a strong curvature allowing for smooth flexion and extension, while a weak curvature is exhibited in the transverse plane, where mobility is almost completely locked. Apart from the role of the nonspheroidicity of the joint in limiting the physiological range of motion, we propose that the double, "strong and weak", curvature is additionally involved in driving fingers' luxations under severe accidental loads, as a way to prevent more serious damages of the articulation. In particular, guided by the observation of the abnormal deviation of phalanges led by luxations under both compressive and tensile extreme forces, we here interpret luxations as an elastic equilibrium bifurcation phenomenon. To this aim, an ad hoc conceived mechanical model is introduced, equipped with a generalized slider constraint, characterized by a double curvature in two orthogonal planes (whose projections are shown in Fig. 2). This model allows the analysis of the onset of elastic instability and the transition from compressive to tensile modes of buckling in the resulting all-in-one buckling paradigm.

More in detail, the system comprises two rigid rods interconnected by a hinge-slider joint, which consists of two circular tracks in smooth mutual contact and only allows a relative sliding

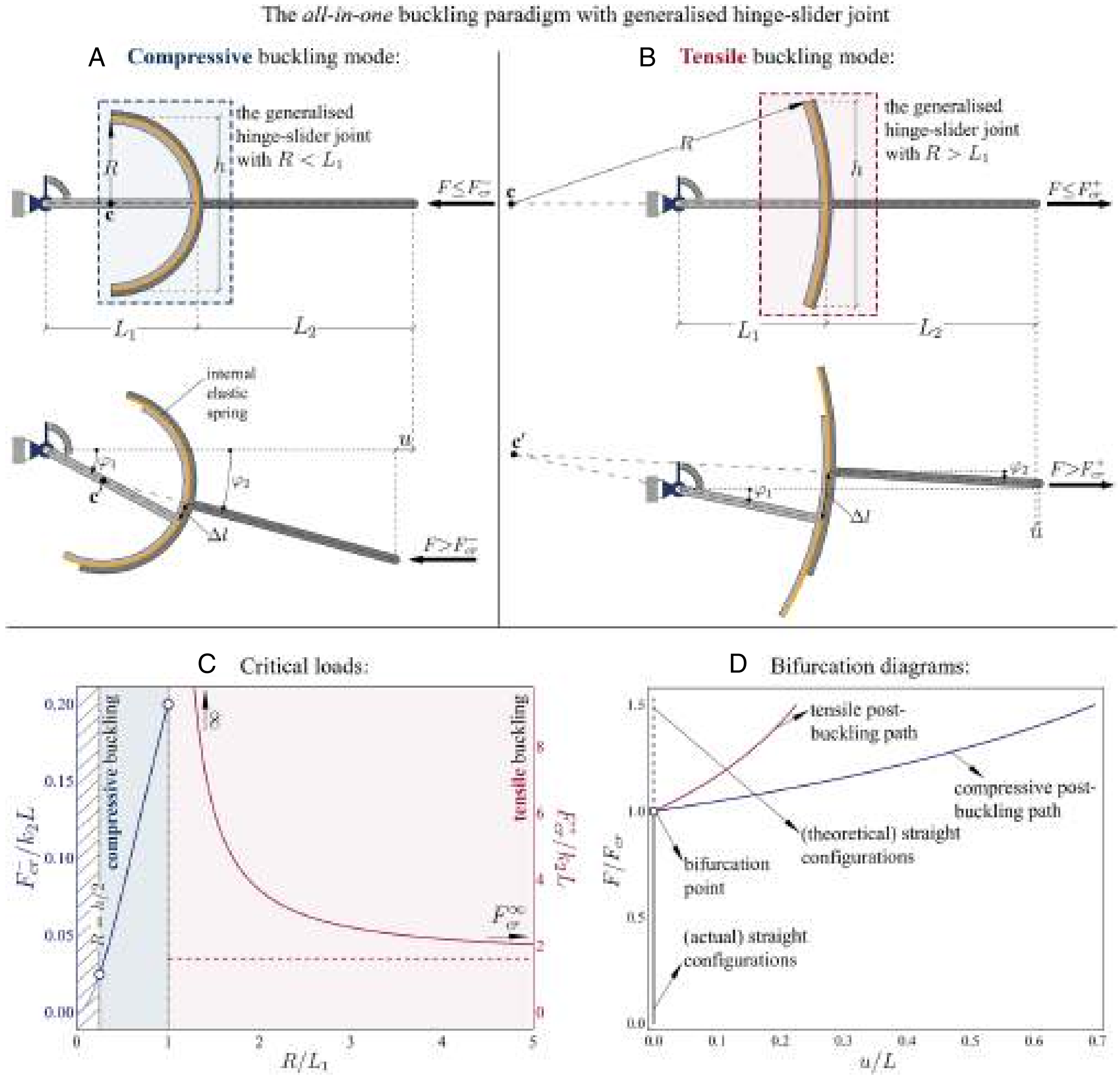

Fig. 2. Structural scheme of the proposed all-in-one paradigm of elastic instability undergoing (*A*) compressive and (*B*) tensile buckling in orthogonal planes as a function of the ratio between the joint's radius and the hinged rod's length. (*C*) (Normalized) critical load versus ratio between the joint's radius and the hinged rod's length, for an illustrative case with $L_1 = L_2 = L/2$, $h = L/2$, and $k_1 = k_2L^2$. Herein, compressive ($h/2 \le R < L_1$) and tensile ($R > L_1$) buckling domains are evidenced, along with the geometrically incompatible region where $R < h/2$. Also, the divergence of the tensile critical load for $R/L_1 \to 1$ is highlighted as well as its asymptotic value $F_{cr}^{\infty} = k_2L/2 + \sqrt{k_2\left(k_2L^2 + 4k_1\right)}/2$ corresponding to the limit of straight slider, i.e., $R/L_1 \to \infty$. (*D*) Examples of equilibrium bifurcation diagram for both the cases of structure buckling under axial compression (for $R = h/2 = L/4$; blue curve; $F_{cr} = F_{cr}^{-}$) and tension (for $R = 3L/4$; red curve; $F_{cr} = F_{cr}^{+}$), by starting from an initially stable straight configuration (solid black curve) that becomes unstable (dashed black curve) beyond the bifurcation point.

without detachment (30). The extent of sliding is elastically contrasted by an internal spring, circumferentially arranged along the tracks, and the overall equilibrium of the structure is enforced by the presence of an elastic hinge, acting at one of the ends and so realizing a cantilever configuration. Such a joint reduces to a traditional hinge in the limit case of vanishing ratio between the radius of curvature and the rods' length (28), while it becomes a flat slider as in ref. 24 in the complementary condition of ideally infinite ratio.

As sketched in Fig. 2, when loaded through a dead axial force F at its free end, the considered system can exhibit both compressive and tensile buckling, the first occurring in the plane where the radius of curvature of the joint is shorter than the hinged rod (strong curvature plane), while the second taking place in the orthogonal direction, where the center of relative rotation between the rigid tracts falls beyond the hinge (weak curvature plane). In the figure, $\mathbf{c}$ and $\mathbf{c}'$ denote the rotation centers of the generalized joint in the reference and current configuration, respectively, L_1 and L_2 are the lengths of the rigid rods, while R and h are the radius of curvature and the transverse size of the slider, such that $h \leq 2R$. When sufficiently high, the external load induces buckling through the nontrivial deformation modes shown in Fig. 2 *A* and *B* for compression and tension, respectively. In both cases, the kinematics is governed by two degrees of freedom, which can conveniently be identified with the angles φ_1 and φ_2, describing the clockwise rotation of the rods with respect to the horizontal direction. The horizontal displacement of the right end, say u, can be written with reference to its absolute value as

$$u = |\,(R + L_2)\cos\varphi_2 - (R - L_1)\cos\varphi_1 - L|, \qquad [1]$$

where $L = L_1 + L_2$, while the elongation Δl of the spring associated with the slider is

$$\Delta l = R\,(\varphi_1 - \varphi_2)\,. \qquad [2]$$

Among the compatible deformation modes, equilibrium configurations follow from the stationarity of the total potential energy

$$\Pi = \frac{k_1}{2}\varphi_1^2 + \frac{k_2}{2}\Delta l^2 - Fu, \qquad [3]$$

where k_1 is the stiffness of the rotational spring constraining the hinge and k_2 is the stiffness of the spring acting along the slider, both assumed as linear elastic. Stationarity of Π leads to the system of nonlinear equations

$$\begin{cases} \left(1 + \frac{k_1}{k_2 R^2}\right)\varphi_1 - \varphi_2 - \frac{F}{k_2 R}\left(1 - \frac{L_1}{R}\right)\sin\varphi_1 = 0 \\ \varphi_1 - \varphi_2 - \frac{F}{k_2 R}\left(1 + \frac{L_2}{R}\right)\sin\varphi_2 = 0 \end{cases}, \qquad [4]$$

which admits bifurcation of the equilibrium solution for both the conditions of strong and weak curvature. In particular, bifurcation loads can be derived as a nontrivial solution of the linearized equations [**4**] with respect to the Lagrangian variables φ_1 and φ_2, thus yielding a quadratic equation for the axial force F,

$$a_0 F^2 - a_1 F - a_2 = 0, \qquad [5]$$

with coefficients a_0, a_1, and a_2 given by

$$\begin{aligned} a_0 &= (R - L_1)(R + L_2), \\ a_1 &= k_1(R + L_2) + k_2 R^2 L, \\ a_2 &= k_1 k_2 R^2. \end{aligned} \qquad [6]$$

A tensile buckling force, F_{cr}^{+}, is found, which refers to the weak curvature plane (where $R > L_1$), plus three compressive bifurcation forces, the lowest of which, occurring in the strong curvature plane (where $R < L_1$), can be identified as "critical", F_{cr}^{-}. This implies that the mechanical model predicts deviations from its straight configuration once tensile and compressive loads overcome the respective critical thresholds

$$F_{cr}^{\pm} = \frac{\sqrt{a_1^2 + 4a_0 a_2} \pm a_1}{2a_0}, \qquad [7]$$

where $a_1^2 + 4a_0 a_2 \geq 0$ when $L_2 \geq L_1$.

As an illustrative case of the proposed all-in-one buckling paradigm, the critical load is plotted in Fig. 2*C* as a function of the ratio between the radius of the sliding joint and the hinged rod length. It is possible to observe that the structure switches from compressive to tensile buckling when the radius R exceeds the length L_1, $R = L_1$ thus representing a limit condition for which tensile buckling does not occur. Furthermore, bifurcation diagrams, numerically obtained as solutions of equations Eq. **4**, are reported in Fig. 2*D* for both compressive and tensile buckling.

Finally, it is worth noticing that straightforward calculations allow to estimate the bending stiffness of the considered system at the joint level as $k_2 R^2$. This indicates that the double curvature, characterizing the finger joints' anatomy, naturally provides a flexibility for the sagittal (strong curvature) plane higher than that characterizing the transverse (weak curvature) plane, consistently with the kind of mobility actually observed in fingers.

Cooperation of Elastic Instability and Suction Effect in Luxation of Finger Joints

Finger joints of human hands can be considered hallmark structures for elucidating how the unique ability to experience both compressive and tensile buckling can provide key stress shielding responses to prevent bone, ligaments, and tendons from more serious mechanical damages (31). To show this, the fingers' bone-joint-bone system is structurally modeled by following the above-illustrated concept of all-in-one buckling paradigm, as reported in Fig. 3 with reference to the transverse and sagittal anatomical planes. Therein, to account for the stabilization role played by the capsular and extracapsular fibrous tissues surrounding the articular joint, elastic bands connecting the ends of the slider are additionally incorporated in the mechanical model. Furthermore, anatomical considerations suggest the possibility that a small detachment between the epiphyses of the joined bones may occur under distracting loads. This feature is implemented in the model and coupled with the intracapsular suction effect that opposes the separation between articular surfaces (9–14, 32). Investigation of the system's response under uni-axial load yields the identification of tensile and compressive buckling as mechanisms dominating lateral and dorsal/volar luxations, respectively, occurring in the transversal and sagittal planes of the hand (16). The progression of the dislocation process after luxation, falling beyond the scope of the present study, is neglected.

Lateral Luxation Ruled by Tensile Buckling along the Weak Curvature. The mechanical models illustrated in the Fig. 3, *Left* show the tensile buckling mechanism through which finger joints undergo lateral dislocations in the horizontal anatomical plane, where the bones' interface is characterized by the weak curvature. In particular, starting from a resting condition, the action of a distracting force F initially produces a small axial separation between the articulating bone heads, remaining within physiological limits. Then, as the magnitude of the load surpasses a critical threshold, say F_{cr}^{+}, the two epiphyses dislocate by deviating laterally with respect to their straight anatomical configuration.

The kinematic description of this bifurcation mode is characterized by three Lagrangian parameters, namely the rotations φ_1 and φ_2 of the rigid rods—representing bone segments—with respect to the horizontal direction, and the relative displacement Δ between their ends at the joint level. Therefore, equilibrium configurations requiring stationarity of the total potential energy

$$\Pi = \frac{k_r}{2}\varphi_1^2 + \frac{EA}{2l}\left[(l'_+ - l)^2 + (l'_- - l)^2\right] + \Upsilon_{ic} - Fu, \qquad [8]$$