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The effect of orthoses on the kinematics of the trapeziometacarpal, scaphotrapeziotrapezoidal, and radioscaphoid joints

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Abstract

The in vivo effect of four different types of thumb and thumb-wrist orthoses on the three-dimensional kinematics of the trapeziometacarpal (TMC), scaphotrapeziotrapezoidal (STT) and radioscaphoid joints was quantified using computed tomography (CT). Eighteen healthy female volunteers were recruited. The dominant hand of each subject was scanned in four thumb and wrist positions, each in three conditions: without orthosis, with a thumb orthosis (Push Ortho and immediate fitting, IMF) and with a thumb-wrist orthosis (Ligaflex Manu and IMF). CT images were analyzed and rotations relative to the more proximal bone were expressed in a joint-specific coordinate system. Without orthosis, the largest STT rotations were observed during radioulnar deviation of the wrist and the STT range of motion (ROM) was significantly lower during wrist flexion-extension. All tested orthoses caused a significant reduction of the ROM at each joint compared to free motion. Significant differences in movement reduction were observed between prefabricated and IMF orthoses.The IMF thumb-wrist outperformed the Ligaflex Manu in terms of immobilization of the radioscaphoid joint. In addition, the IMF thumb orthosis immobilized the TMC joint significantly better during thumb abduction and adduction than the Push Ortho. We found that different types of thumb and thumb-wrist orthotics are effective in reducing joint mobility. While this reduction tends to be higher using IMF compared to prefabricated orthoses, this effect is only significant for the radioscaphoid and TMC joint. The finding that thumb movements do not induce large STT rotations suggests that the thumb does not need to be immobilized in case of isolated STT osteoarthritis.

KEYWORDS
brace, osteoarthritis, splint, thumb, wrist

1 | INTRODUCTION

Splinting of the thumb and wrist has proven to be an effective and widely used approach to immobilize pathological joints.[1] This conservative treatment applies to many different indications, for example, ligament laxity, post traumatic care, or early stages of osteoarthritis (OA) Eaton-Littler stage I or II[2]. In case of OA, the aim of the orthosis is to reduce joint inflammation and pain by providing rest, immobilization and support during heavy joint loading activities as well as to avoid or correct subluxation and deformity of the thumb.[3-5]

Splinting options for the treatment of thumb and thumb-wrist pathologies are numerous and range from short opponens to long opponens types, also called thumb or thumb-wrist orthoses respectively. Thumb orthosis includes the trapeziometacarpal (TMC) and first metacarpophalangeal (MCP) joints or only the TMC joint, while thumb-wrist orthoses also incorporate the wrist.[6,7] In addition, orthoses can be divided into two main groups, prefabricated and immediate fitting (IMF). Prefabricated orthoses are available in different materials (eg: neoprene, PE,…), while IMF orthoses are custom-molded in a thermoplastic material. The choice of the most suitable orthosis for a specific patient depends on different parameters including the type of pathology, severity of symptoms and, in case of chronic disorders such as OA, the specific need of the patient. For TMC OA, the most commonly used orthosis is a custom-made thumb orthosis[8] with the Push Ortho thumb brace as a popular prefabricated alternative.[9] For the treatment of scaphotrapeziotrapezoidal (STT) OA, splint designs vary from thumb to thumb-wrist types.[10]

Ideally, thumb and thumb-wrist orthoses should provide maximal support and immobilization of the affected joints while leaving other joints of hand and wrist as free as clinically desirable, in order to maintain hand and wrist function as much as possible.[7,11,12] Comfort during activities of daily living is key to the patient's treatment compliance and a cornerstone of therapeutic success. A thorough understanding of wrist and thumb kinematics, together with an individual assessment of carpal behavior, are key to select the optimal orthosis which increases functionality as well as provides adequate immobilization. Several qualitative studies have been performed to evaluate the effects of different types of orthoses on pain and function, with a primary focus on splinting of the TMC joint.[1,13-16] On the contrary, the effect of orthotics on carpal bone kinematics remains unclear. Stabilizing effects of orthoses using an external motion-tracking system were investigated by Hamann et al. demonstrating that stabilization and functionality are opposing demands. Higher immobilization coincides with lower hand functionality,[17] however additional research is needed to consolidate these findings. The objective of this study is to quantify the effect of multiple thumb and thumb-wrist orthoses on the in vivo kinematics of the TMC, STT and radioscaphoid joints, joints which are prone to OA and are commonly treated with orthotics in early stages of the disease.

2 | MATERIALS AND METHODS

2.1 | Participants

After approval by the Medical Ethical Committee of the University of Leuven (Belgium, B322201732890), 18 healthy female volunteers between the age of 18 and 60 years were recruited (mean age: 26.8 years; range 19-56 years; 17 right-handed and 1 left-handed). Each volunteer underwent a clinical examination to assess thumb and wrist joint integrity. The examination consisted of a Kapandji score, a grinding test, deep palpation of the TMC and STT joints. Exclusion criteria consisted of pain during the clinical exam, previous thumb and/or wrist injury and pathologies that could affect joint kinematics.

2.2 | Orthotics

Each participant was fitted subsequently with a thumb and thumb-wrist orthosis. Participants were randomly assigned to either the IMF orthosis group (n = 6) or the prefabricated orthosis group (n = 12) (Figure 1).The IMF orthoses were fitted by a certified technician using the current standards. For the prefabricated splints, the Push Ortho Thumb Brace CMC (Figure 1A) and Thuasne Ligaflex Manu (Figure 1C) were used, based upon their widespread use in clinical practice. The velcro straps of the splints were tensioned to 2 kg and were not removed or readjusted during the entire duration of the data acquisition.

2.3 | Imaging protocol

The dominant hand of each subject was scanned from the distal part of the radius up to the metacarpophalangeal joints, in two movement pairs of the thumb: from maximal active, extension to flexion and from radial adduction to abduction, and two movement pairs of the wrist: from maximal active extension, to flexion and from ulnar to radial deviation (Figure 2). A custom-designed, radiolucent, polycarbonate rig developed by Orthopaedic Bioengineering Laboratories, Brown University (Rhode Island Hospital, Providence, RI) as used in the previous publications[18-20] was utilized to standardize the motion of the thumb (Figure 2A). To standardize the movements of

FIGURE 1 Illustration of the different types of orthoses used in the study. A, Push Ortho thumb brace CMC. B, Thumb orthosis, immediate fitting (Orfit industries; 2 mm). C, Thumb-wrist orthosis, Thuasne Ligaflex Manu. D, Thumb-wrist orthosis, immediate fitting (Orfit industries; 3 mm) [Color figure can be viewed at wileyonlinelibrary.com]

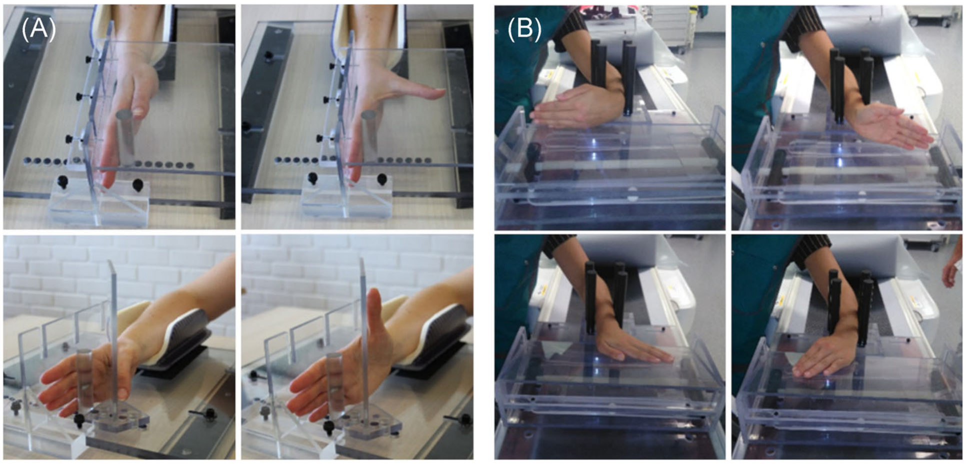

FIGURE 2 Illustration of the custom-made, radiolucent rigs used to standardize the position of the thumb (A) and wrist (B) during CT-scanning. A, Positions of the thumb: adduction-abduction (TAA; top row) and flexion-extension (TFE; bottom row). B, Positions of the wrist: flexion-extension (WFE; top row) and ulnar-radial deviation in 15° of dorsiflexion (RUD; bottom row). CT, computed tomography; RUD, wrist ulnar-radial deviation; TAA, thumb adduction-abduction; TFE, thumb flexion-extension; WFE, wrist flexion-extension [Color figure can be viewed at wileyonlinelibrary.com]

the wrist, we developed a new custom-made rig in which the distal part of the forearm was fixed in 0° of pro-supination, while the hand was placed on a height-adjustable plate (Figure 2B). This height adjustment was used to line up the third metacarpal with the radius. During radio-ulnar deviation, a wedge of 15° accounted for the 15° of dorsiflexion of the wrist as applied during splinting. During all movements of the wrist, the thumb was positioned against the radial side of the second metacarpophalangeal joint (full adduction).

The volunteers were instructed to perform maximal excursion with either thumb or wrist while maintaining contact with the radiolucent rig to restrict motion to one plane. They were asked to perform maximally without moving the hand and thumb during the scan time.This resulted in eight joint positions and four-movement pairs, thumb flexion-extension (TFE), thumb adduction-abduction (TAA), wrist flexion-extension (WFE), and wrist ulnar-radial deviation (RUD). Each group of volunteers, IMF and prefabricated, was scanned in these eight positions using a thumb and thumb-wrist orthosis. In addition, unconstrained joint kinematics (ie, without splint) were collected to provide control of each volunteer. The scan protocol was designed and executed using the ALARA principle. The computed tomography (CT)-scans were taken using a 64 slice Discovery HD 750 CT scanner (GE Healthcare, Little Chalfont, UK) at the hospital AZ Groeninge, Kortrijk, Belgium. Imaging parameters included a tube setting of 100 kV and 156 mA, slice thickness of 0.625 mm, pixel size 0.34 mm. The radiation dose for one static CT scan was estimated to be 6.85 mGy (CT dose index volume).

2.4 | Image processing and data analysis

Dedicated image processing software (Mimics 20.0 Materialise, Leuven, Belgium) was used to semi-automatically segment the radius, scaphoid, trapezium, and MC1 of each scan and to create three-dimensional (3D) surface models of each bone in each position. The third metacarpal (MC3) was also segmented to measure the amount of wrist movement. In the case of left-sided wrists, the bones were mirrored to digitally create a uniform set of right wrists to facilitate data analysis.

In order to quantify the kinematics of the radioscaphoid, STT, and TMC joints, three independent coordinate systems were used: (a) a radius-based, (b) a scaphoid-based, and (c) a TMC-joint-based coordinate system (Figure 3). The radius-based coordinate system, in agreement with ISB standards,[21] was defined using three anatomical landmarks on the radius: (a) the lowest point on the distal border of the ulnar notch (bordering the lunate fossa); (b) the proximal border of the ulnar notch; and (c) the tip of the radial styloid. These landmarks define a local coordinate system with the origin placed at (a), the y-axis defined as the vector pointing from (a) to (b), the z-axis being perpendicular to the y-axis and the line parallel to the y-axis passing by (c), and the x-axis as the vector perpendicular to the y-and z-axes.[19] The rotations of the scaphoid and MC3 were expressed in the radius-based coordinate system. The scaphoid-based coordinate system was defined using the center of gravity and the inertia axes of the scaphoid.[22] The kinematics of the STT joint was reported by expressing the movement of the trapezium relative to the mathematically-fixed scaphoid.[23] Finally, a coordinate system based on the shape of the articular surfaces of the trapezium and MC1 was used to quantify the movement of the MC1 relative to the trapezium.[24] The coordinate systems were defined on one scan per volunteer and used for the calculations of the entire scan series to exclude inaccuracies induced by individual coordinate system demarcation.

The 3D joint rotations of the scaphoid, trapezium, MC1, and MC3 during the four-movement pairs (two for the thumb: TAA, TFE, and two for the wrist: WFE, RUD) were calculated using custom Python code and expressed in their respective coordinate system. The sign of the rotations is based on the joint coordinate system and

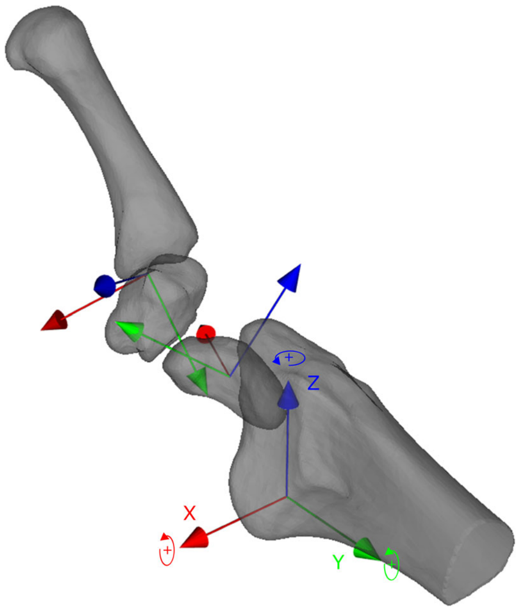

FIGURE 3 Coordinate systems of the radioscaphoid, STT and TMC joint. Movements of the scaphoid are expressed in the radius-based coordinate system (radioscaphoid joint). X-axis: ulnar (+) –radial (-) deviation axis (dorsal-to-palmar), Y-axis: internal (+) -external (-) rotation axis (distal-to-proximal) and the Z-axis: flexion (+) -extension (-) axis (ulnar-to-radial). Movements of the trapezium are expressed in the scaphoid-based coordinate system (STT joint). X-axis: flexion (-) -extension (+) axis, Y-axis: internal (+) -external (-) rotation axis and the Z-axis: ab (+) -adduction (-) axis and movements of the MC1 are expressed in the TMC joint coordinate system. X-axis: ab (-) -adduction (+) axis, Y-axis: internal (+) -external (-) rotation axis, and the Z-axis: flexion (+) -extension (-) axis. STT, scaphotrapeziotrapezoidal; TMC, trapeziometacarpal [Color figure can be viewed at wileyonlinelibrary.com]

the right-hand rule, a rotation direction can be determined since a specific movement sequence is performed. The rotation reductions were calculated as the difference between movement, of the thumb and wrist, without and with an orthosis for each individual volunteer. Tait-Bryan angles were used in the ZYX order to calculate the rotations. The 3D models of the bones were registered onto each other using iterative closest point and coherent point drift registration techniques.[25,26] The translations of (meta)carpal bones, defined as a translation along the helical axis, were found to be very small during thumb and wrist movement,[27] therefore only rotations were reported in this study.

2.5 | Statistics

A one-way repeated measures analysis of variance was performed to compare the effect of an orthosis on the joint rotations in the IMF and prefabricated group. In case of significance, a posthoc analysis using a paired *t*-test was used to determine the significance between the different conditions, that is, control group, thumb orthosis and thumb-wrist orthosis (Table 1). Significance in rotation reduction between the prefabricated and IMF group was tested for using an unpaired *t*-test (Table 2), as well as the difference between the thumb IMF and thumb-wrist prefab orthoses. The data were checked for normality using a Shapiro-Wilk test. In the case of non-normality (n = 1), a Wilcoxon signed-rank test was used, or a Mann-Whitney U test was applied to test for significance in case of a paired and unpaired test respectively. The alpha level was set at 0.05, no reduction for multiplicity was applied. All data are presented as mean with their 95% confidence interval. Statistical analysis was done using Scipy 1.1.0 and Statsmodels 0.10.1.

3 | RESULTS

A comprehensive summary of the quantitative data is provided in Tables 1 and 2. The full dataset can be found in (Tables S1, S2, and S3).

3.1 | Unconstrained thumb and wrist kinematics

During wrist motion (WFE and RUD), the largest rotations in the radioscaphoid joint were seen around the flexion-extension axis

TABLE 1 3D kinematics with IMF and Prefab orthoses with respect to no immobilization ("Without")

				Rotation means [°] ±C.I. 95%				
Orthosis	Joint	Mov.	Axis	Without (n = 18)	IMF (n = 6)	*P*-value	Prefab (n = 12)	*P*-value
Thumb	TMC	TAA	X	−38.8 ± 5.5	−18.3 ± 4.7	.02*	−31.0 ± 6.4	<.001*
		TFE	Z	−30.9 ± 5.3	−7.1 ± 6.8	.04*	−17.3 ± 5.6	<.001*
Thumb-Wrist	STT	RUD	X	45.4 ± 4.7	19.9 ± 7.9	<.001*	28.7 ± 7.6	<.001*
		WFE	Z	−23.1 ± 4.4	−2.5 ± 1.7	<.001*	−3.2 ± 2.0	<.001*
	Rad. Carp.	RUD	Z	37.9 ± 4.4	11.4 ± 5.3	<.001*	23.6 ± 6.1	<.001*
		WFE	Z	−79.0 ± 3.3	−12.3 ± 6.0	<.001*	−31.1 ± 7.3	<.001*

Note: Statistical significance (*P*-value) is given of difference between Without and IMF, and between Without and Prefab immobilization. Abbreviations: 3D, three dimensional; IMF, immediate fitting; RUD, wrist ulnar-radial deviation; TAA, thumb adduction-abduction; TFE, thumb flexion-extension; WFE, wrist flexion-extension.

TABLE 2 Average reduction in ROM obtained by IMF and Prefab orthoses with respect to no immobilization of the TMC, STT and radioscaphoid joints

				Reduction means [°] ±C.I. 95%		
Orthosis	Joint	Movement	Axis	IMF (n = 6)	Prefab (n = 12)	*P*-value
Thumb	TMC	TAA	X	22.0 ± 12.6	7.4 ± 3.2	.01*
		TFE	Z	22.3 ± 13.1	15.2 ± 3.8	.35
Thumb-Wrist	STT	RUD	X	22.7 ± 2.4	18.1 ± 5.1	.14
		WFE	Z	23.4 ± 8.5	18.5 ± 4.2	.34
	Rad. Carp.	RUD	Z	27.4 ± 7.4	15.6 ± 3.3	.02*
		WFE	Z	67.1 ± 8.1	47.7 ± 10.0	.01*

Note: Statistical significance (*P*-value) is shown of the difference in reduction in ROM between IMF and Prefab orthoses.
Abbreviations: IMF, immediate fitting; ROM, range of motion; RUD, wrist ulnar-radial deviation; STT, scaphotrapeziotrapezoidal; TAA, thumb adduction-abduction; TFE, thumb flexion-extension; TMC, trapeziometacarpal; WFE, wrist flexion-extension.

(−79.0 ± 3.3° and 37.9 ± 4.4°, resp.). During the RUD of the wrist, this flexion-extension of the radioscaphoid joint was combined with a marked radioulnar deviation of 23.2 ± 2.6° (Figure 4A). RUD of the wrist also induced the largest rotations in the STT joint, with 45.3 ± 4.7° extension and −39.3 ± 3.2° adduction. In contrast, WFE caused significantly smaller rotations around both axes, amounting to respectively −5.8 ± 5.6° flexion and −23.1 ± 4.4° abduction (Figure 4B).

During thumb motion (TAA and TFE), STT rotations around all axes were smaller or equal to 10°, with the largest motion occurring around the flexion-extension axis in the case of TFE (10.4 ± 2.4°) (Figure 4B). However, both thumb movements resulted in large TMC rotations, with the largest rotations occurring around the abduction-adduction axis for TAA (38.8 ± 5.5°) and around the flexion-extension axis for TFE (−30.9 ± 5.3°).

3.2 | Impact of thumb-wrist orthoses on the radioscaphoid kinematics

Both thumb-wrist orthoses (IMF and Ligaflex Manu) led to a significant reduction in the range of motion (ROM) of the radioscaphoid joint during wrist movements (RUD and WFE) compared to unconstrained motion (Table 1; Figure 5). This effect was significant around all three axes of rotation ($P < .05$, Table 1). During WFE, the IMF orthoses decreased the rotation of the radioscaphoid joint around the flexion-extension axis by 67.9 ± 8.1°, which is significantly higher compared to the movement reduction obtained by the Ligaflex Manu orthosis, which is 47.7 ± 10.0°. During RUD there was also a significant reduction difference between the two orthoses (Table 2). This higher immobilization performance of the IMF orthosis compared to the LigaFlex Manu is also partially evidenced by the considerable reduction in overall wrist motion, as measured by the MC3 rotations. During wrist RUD, there was no significant difference in the radioulnar deviation of MC3 between IMF and prefabricated thumb-wrist orthoses (−22.2 ± 8.3°; −31.5 ± 7.1° resp. $P = .12$). While during WFE, flexion-extension of the MC3 amounted to −14.6 ± 5.5° and −34.4 ± 8.2° ($P = .01$), respectively.

3.3 | Impact of thumb-wrist orthoses on STT kinematics

During RUD, both thumb-wrist orthoses (IMF and Ligaflex Manu) significantly reduced the ROM of the STT joint around the flexion-extension and abduction-adduction axes ($P < .001$). Similarly, both orthoses also led to a significant decrease in the STT joint rotations around the abduction-adduction axis during WFE ($P < .001$) (Table 1). However, there was no significant difference between the immobilization performance of the IMF and the Ligaflex Manu thumb-wrist orthoses at the level of the STT joint (Table 2).

3.4 | Impact of thumb and thumb-wrist orthoses on TMC kinematics

Both thumb orthoses (Push Ortho and IMF) resulted in a significantly lower ROM of the TMC joint around the main axes of rotation, being the abduction-adduction axis for TAA and flexion-extension axis for TFE compared to unconstrained motion (Figure 5). For TAA, the Push Ortho reduced the ROM of MC1 by 7.4 ± 3.2° around the ab-adduction axis, which was significantly lower than the reduction of 22.0 ± 12.6° obtained by the IMF orthosis ($P < .01$) (Table 2). For TFE, the orthoses decreased the ROM with 15.2 ± 3.5° (Push Ortho) and 22.3 ± 13.1° (IMF), and no significant difference between the Push Ortho and IMF thumb orthoses in immobilization performance could be observed during TFE at the level of the TMC joint (Table 2).

When we compare the immobilization performance of the two prefabricated orthoses (Ligaflex Manu and Push Ortho) with respect to limiting TMC joint motion, we found that during TFE, the Ligaflex Manu orthosis provided a significantly higher movement reduction around the flexion-extension axis (21.8 ± 5.3°) compared to the Push Ortho (15.21 ± 3.84°; $P = .02$). During TAA, the obtained reductions in ROM around the adduction-abduction axis were also significantly higher with the Ligaflex Manu compared to the Push Ortho (21.7 ± 5.9° and 7.4 ± 3.2°, resp.; $P < .001$).

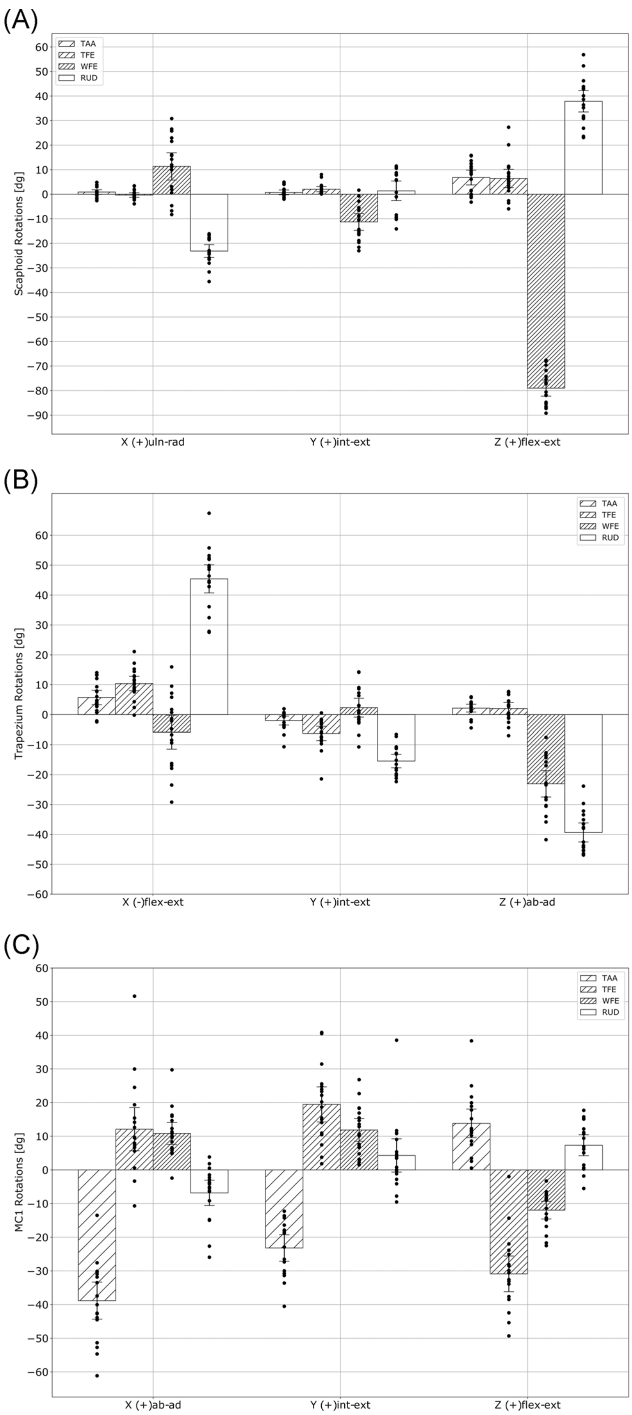

FIGURE 4 3D kinematics of A, the scaphoid (radioscaphoid joint), B, the trapezium (STT joint) C, the MC1 (TMC joint) without orthoses during thumb abduction (TAA), thumb extension (TFE), wrist extension (WFE) and wrist radial deviation (RUD). Values depicted are the mean range of motion in each plane (XYZ), 95% C.I., and the individual data points. 3D, three dimensional; STT, scaphotrapeziotrapezoidal; TMC, trapeziometacarpal

Finally, no significant differences in TMC joint rotations were found between the Ligaflex Manu and thumb IMF orthosis during thumb movements (Table S3; $P > .05$).

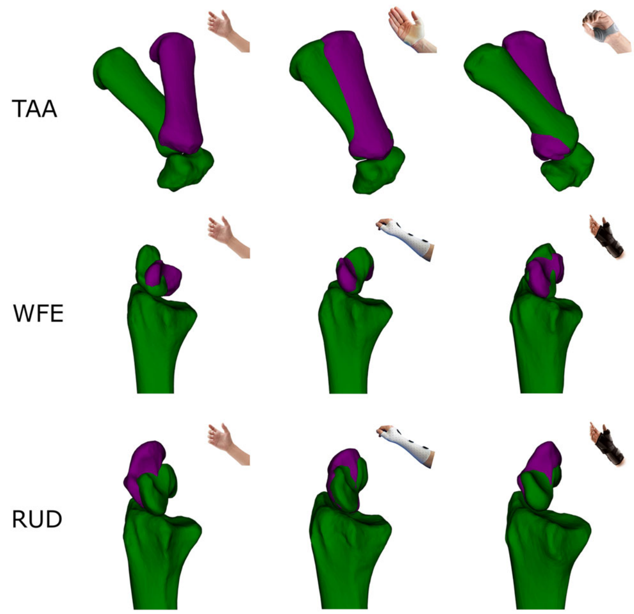

FIGURE 5 Overview of the significant joint reductions. In purple the initial position and in green the resulting position of the bones [Color figure can be viewed at wileyonlinelibrary.com]

4 | DISCUSSION

Splinting is a widely used conservative treatment for early stages of TMC and STT OA, however, to date the underlying biomechanical and analgesic mechanisms remain largely unclear. This study addresses this hiatus by measuring in vivo kinematics of the TMC, STT and radioscaphoid joints in healthy volunteers while wearing different types of orthoses.

4.1 | Immobilization performance of the different orthoses

The thumb-wrist IMF orthosis leads to a significantly stronger reduction of radioscaphoid rotations around the flexion-extension axis than the Ligaflex Manu orthosis, both during WFE and RUD (Table 1). This can be explained by the larger stiffness and better fit of the IMF orthosis compared to the prefabricated orthosis, resulting in a smaller ROM of the wrist. This difference in movement restriction of the wrist is also evidenced by the corresponding rotations of the MC3, which give an indication of overall wrist motion.

In contrast to the radioscaphoid joint, there is no significant difference between the immobilization performance of the thumb-wrist IMF and Ligaflex Manu orthoses at the level of the STT joint. This is likely due to the fact that the influence of wrist motion on the STT joint is smaller than on the radioscaphoid joint.

At the level of the TMC joint, the thumb IMF immobilized the TMC joint more than the Push Ortho splint. The major difference between these two orthoses, that can help to elucidate these findings, is the location of the trimline at the thumb. The trimline of the IMF splint is located proximal of the MCP joint, while for the Push Ortho orthosis it is located proximal of the MCP joint. It is reasonable to assume that a more distal trimline on the thumb will have a positive effect on the immobilization of the thumb and hence of the TMC joint. These conclusions are also reflected in the comparison between the thumb (Push Ortho) and thumb-wrist (Ligaflex Manu) prefabricated splints where we found that the TMC joint was significantly better immobilized with the Ligaflex Manu. Nevertheless, studies[9,28] that compare the effect of a thumb IMF and the Push Ortho splint on pain, hand function and patient satisfaction suggest that patients may prefer the Push Ortho splint. This illustrates the complex relationship between joint immobilization, pain reduction and patient preferences.

4.2 | Effectively reducing STT joint mobility

Osteoarthritis of the STT joint is the second most frequent OA location in the wrist.[29] In up to 90% of cases, STT OA is associated with OA at the more proximal TMC joint,[30] with a prevalence of 2% to 16% for isolated STT OA.[31] Conservative treatment of STT OA consists of activity alteration, splinting, intra-articular steroid injections, NSAID and physiotherapy. Currently, thumb, as well as thumb-wrist orthoses, are used for splinting of the STT joint.[10] However, our findings suggest that rotations of the STT joint are primarily induced by wrist motion while the STT joint does not move much (≤10°) during the motion of the thumb.

The observation that the thumb causes limited rotations in the STT joint can be understood when looking at the positioning of the trapezium in the carpus. The trapezium is firmly connected to the trapezoid and MC2 via the trapeziotrapezoid ligament and movement between the trapezium and trapezoid is small.[23] The finding that movement in the STT joint is primarily induced by wrist motion could suggest that the thumb does not need to be immobilized in case of isolated STT joint pathology (eg, primary STT OA). Furthermore, the results indicate that unconstrained wrist motion leads to marked rotations of the STT joint, which are most pronounced during RUD and are substantially smaller during WFE. These findings are consistent with the data reported by Sonenblum et al, who describes a greater amount of trapezium motion during wrist ulnar deviation and significantly less in WFE.

When translating these results to the design of an orthosis for isolated STT pathology, the results suggest that a freely movable thumb would effectively immobilize the STT joint, while also allowing a higher functionality for the patient. Moreover, a thumb-wrist orthosis that restricts RUD and allows for some WFE could further increase the functionality and comfort of this specific patient group. The difficulty lies in determining what amount of movement reduction is clinically desirable in a given condition, as well as finding a good balance between movement reduction and comfort. Immobilization is needed to reduce pain and inflammation, however, total immobilization removes the cyclic hydrostatic pressure that is crucial in maintaining cartilage health.[32,33] An orthosis that optimally balances immobilization, pain, and comfort would be an important improvement for the patient while also being more effective in OA treatment than current splinting options. Further research should be done to investigate the clinical applicability of different orthosis designs.

4.3 | Critical considerations

Given the high inter- and intra-individual variability in joint mobility and motion patterns, the use of a rig was essential to standardize the positions of wrist and thumb and allow comparison between subjects. Indeed, even with the rig, we did observe a high inter-individual variability in joint ROM. Another source of variability can be found in the maximal active movements the volunteers were asked to do. Obviously, a larger excursion at the wrist or thumb will be associated with larger rotations at the corresponding joints. In the case of WFE and RUD, we found a linear relationship between MC3 rotations and radioscaphoid rotations around the z-axis, with an R^2-value of 0.94 and 0.56 respectively.

In addition to the substantial variability, there are some limitations that should be taken into account when interpreting the results discussed above. Most importantly, we worked with small sample size and included solely healthy female volunteers in the study. We specifically chose to work with healthy volunteers to exclude the important changes in bone morphology that accompany advanced stages of OA, as previous studies show that such morphological deformations can have a substantial effect on the joint kinematics.[19] We do not expect the 3D kinematics of the TMC, STT, and radioscaphoid to be significantly different in other healthy age groups or in male subjects, given that there are no pronounced differences in joint morphology,[34,35] yet further research has to be done to confirm these hypotheses.

This study is the first to quantify the effect of different orthotics on the in vivo kinematics of the radioscaphoid, STT and TMC joints during wrist and thumb motion and represents a first step towards the understanding of the influence of orthotics on the joint kinematics of the thumb and wrist. A thorough comprehension of thumb and wrist kinematics, combined with an individual assessment of carpal behavior will enable physicians to equip patients with more optimally designed orthoses that provide increased functionality with sufficient immobilization.

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AUTHOR CONTRIBUTIONS

MV: conception and design, drafting of the article, critical revision of the article for important intellectual content, final approval of the article, provision of patients, obtaining of funding , collection and assembly of data. FS: conception and design, critical revision of the article for important intellectual content, final approval of the article, obtaining of funding. EEV: Conception and design, interpretation of the data, critical revision of the article for important intellectual content, final approval of the article, obtaining of funding. All the authors have read and approved the final submitted manuscript.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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