


## RESEARCH ARTICLE

# Musculoskeletal simulation of elbow stability for common injury patterns

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## Abstract

Elbow stability is derived from a combination of muscular, ligamentous, and bony structures. After an elbow trauma the stability of the joint is an important decision criterion for the subsequent treatment. The decision regarding nonoperative/operative care depends mostly on subjective assessments of medical experts. Therefore, the aim of this study is to use musculoskeletal simulations as an objective assessment tool to investigate the extent to which failure of different stabilizers affects the elbow stability and how these observations correspond to the assessment from clinical practice. A musculoskeletal elbow simulation model was developed for this aim. To investigate the stability of the elbow, varus/valgus moments were applied under 0°, 45°, and 90° flexion while the respective cubital angle was analyzed. This was performed for nine different injury scenarios, which were also evaluated for stability by clinical experts. With the results, it can be determined by which injury pattern and under which flexion angle the elbow stability is impaired regarding varus/valgus moments. The scenario with a complete failure of the medial and lateral ligaments and a fracture of the radial head was identified as having the greatest instability. The study presented a numerical determination of elbow stability against varus/valgus moments regarding clinical injury patterns, as well as a comparison of the numerical outcome with experience gained in clinical practice. The numerical predictions agree well with the assessments of the clinical specialists. Thus, the results from musculoskeletal simulation can make an important contribution to a more objective assessment of the elbow stability.

## KEYWORDS

AnyBody, elbow stability, musculoskeletal simulation

## 1 | INTRODUCTION

The elbow is the most or second most commonly dislocated joint (following the shoulder) in children and adults, respectively.<sup>1</sup> An elbow trauma can cause injury to the bony, ligamentous, and

muscular stabilizers of the elbow joint, which interact in complex ways. A loss of elbow functionality as a consequence often results in a very severe limitation of mobility and incapability to interaction with the environment effectively. Hence, special examination maneuvers, like the milking maneuver, valgus stress test, or the chair

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push-up test<sup>2</sup> must be performed to diagnose a resulting elbow instability. The stability of the joint is an important decision criterion for the subsequent treatment (e.g., nonoperative vs. operative).<sup>3</sup> Clinical applicability of these tests is often hindered due to pain or patient compliance. While some cases clearly opt for nonoperative or operative treatment categories, treatment selection for many cases is less clear due to the complex interaction of the stabilizers and the diverse injury patterns. In these cases, the decision regarding nonoperative versus operative care depends mostly on the subjective assessment of the medical expert, who is, however, assisted by modern imaging techniques such as the arthro-magnetic resonance imaging.

Elbow stability is derived from a combination of muscular, ligamentous, and bony structures. Depending on their contribution and mechanism, they are divided into primary and secondary as well as static and dynamic stabilizers. In this context, secondary stabilizers adopt a decisive function in the context of injury of the primary stabilizers. There are mainly three primary static structures that stabilize the elbow joint: the ulnohumeral articulation, the medial collateral ligament complex and the lateral collateral ligament complex.

The majority of joint stability is provided by the ulnohumeral anatomy.<sup>4</sup> The anterior part of the medial collateral ligament complex provides stability in mediolateral direction and against valgus moments, whereas the posterior part is responsible for posteromedial rotatory elbow stability.<sup>5–7</sup> Facing external rotation and varus moments, the lateral collateral ligament complex is the primary stabilizer.<sup>8</sup> The muscles that span the elbow and compress the joint are secondary dynamic stabilizers.<sup>9,10</sup> Other secondary, but static, stabilizers are the radial head and capsule of the elbow.<sup>11,12</sup> When considering elbow stability, the influence of forearm rotation cannot be omitted, as it is of decisive importance for valgus/varus laxity. The elbow exhibits a maximum laxity throughout the elbow flexion during the position of the forearm in the neutral position.<sup>13</sup>

As indicated above, the respective roles of individual primary and secondary stabilizers has been investigated in numerous studies. However, to the authors' knowledge, there exists no biomechanical analysis of how different combinations of failures of these stabilizers influence each other in the presence of valgus/varus moments and in which way this loss of stabilizing structures effects overall elbow stability.

Musculoskeletal simulation platforms, such as the AnyBody Modeling System (AMS) (Anybody) provide the ability to analyze a variety of different injury patterns and thus can assist medical specialists in a more objective assessment through a numerical analysis of elbow stability.

Therefore, the aim of this study is to use musculoskeletal simulation to investigate the extent to which failure of different primary and secondary stabilizers affects the elbow stability in neutral position against valgus/varus moments from a biomechanical perspective and how these observations correspond to the assessment from clinical practice. A corresponding musculoskeletal elbow model was developed for this purpose.

## 2 | MATERIALS AND METHODS

### 2.1 | Musculoskeletal model

The developed elbow model was embedded in the AMS Version 7.3 and the AnyBody Managed Model Repository (AMMR) 2.2.2.<sup>14</sup> The AMMR full-body model including the detailed hand model from Engelhardt and Melzner et al.<sup>15,16</sup> was used as a basis. The fact that many of the extrinsic muscles of the hand model originate in the elbow is particularly relevant in this context, as the use of the detailed hand model also allows for a more accurate calculation of the forces acting on the elbow. For the elbow joint, the revolute joint implemented as standard in the AMS was used allowing only one degree of freedom (DOF) (flexion and extension). In contrast to the standard model, the elbow model allows an adjustment of the cubital angle (formed between the axis of a radially deviated forearm and the axis of the humerus). In the AMS standard model, this angle is set to 0°, which corresponds to a cubitus varus deformity; a deformity in which the extended forearm is deviated towards the midline of the body. However, since the literature<sup>17</sup> assumes that a normal cubital angle is between 5° (<5° cubitus varus deformity) and 15° (>15° cubitus valgus deformity), a cubital angle of 10° was defined as standard in the elbow model.

In an anatomical study conducted at the University of Pilsen detailed maps of the upper arm muscles were created.<sup>18</sup> These data, which include the muscle origin and insertion points, as well as the muscle cross-sectional areas, were implemented in the elbow model.

For the ligamentous apparatus, the medial and lateral collateral ligament complexes were implemented using data from prior literature. According to Morrey and An,<sup>19</sup> the lateral ligament complex is composed of the radial collateral ligament (RCL) as well as the medial ligament complex of the anterior and posterior medial collateral ligaments (AMCL and PMCL). The origin and insertion points of these three ligaments, based on a dissection of ten fresh cadaver specimens, were implemented according to Morrey and An<sup>19</sup> for the elbow model. To be able to disentangle the occurring forces in more detail, each band complex was divided into three parts—an anterior, middle, and posterior portion.

Unlike muscles, ligaments cannot actively generate forces themselves. They only passively introduce forces into the multi-body system like a spring. Therefore, the force applied to the system depends strongly on the specific stiffness of the ligaments. Regarding the AMCL, PMCL, and RCL ligaments, Regan et al.<sup>20</sup> measured corresponding force-strain curves of up to seven specimens and representative curves were determined. These curves are used for the analysis of the load acting within the model.

In addition to the stiffness of the ligaments, the length (or the positions of the elbow) at which the ligaments are in a taut state, and thus introduce passive forces to the system, is also essential. The ligament position at which the different parts (anterior, middle, and posterior) of the ligaments can be considered taut in the neutral state

(without additional valgus or varus moments) was also taken from the experimental study of Regan et al.<sup>20</sup> All ligaments were calibrated according to the individual zero-load length  $l_0$  to best fit the tautness-range within the neutral position.

Within the AMS, all joints are defined as ideal joints allowing a certain number of DOFs. However, many biomechanical joints are not ideal and allow small motions between the bones based on acting forces from muscles or ligaments. One example of such a motion is the varus-valgus motion of the elbow joint.

On the one hand, the inverse dynamics approach which the AMS is based on requires motion of the entire system to compute the forces. On the other hand, we need the acting forces to compute the according motion, which leads to a chicken-and-egg problem. This issue is solved by means of the force-dependent kinematics approach,<sup>21</sup> which allows a small rotational deviation for the elbow joint in this case. The passive force created by the ligaments of the elbow stabilizes the joint against free rotation. Therefore, the ligamentous apparatus contributes crucially to resistance against applied valgus/varus moments (though the stabilizing function of capsule and articulation ought to be acknowledged—see Morrey and An<sup>11</sup>).

Morrey<sup>22</sup> separated the elbow joint from four cadaver specimens, leaving only the bone, ligamentous apparatus, and capsule. The joints were then fixed in a corresponding testing machine and the moment acting in the elbow was recorded both for the extension and the 90° flexion for different displacements in the valgus and varus directions. These displacement-load curves were obtained for the intact condition as well as for the complete transection of the lateral and medial ligament apparatus.

This data was incorporated into the elbow model to determine the rotational resistance of the joint in the intact case. This resistance, which results from the capsule and the articulation, was then simulated in the elbow model by a torsion spring in the elbow joint. Since only the values for extension and 90° flexion were determined in the experiment, and thus experimental values for the interval between the two values were missing, the model was based on the assumption of a linear progression between the two interval limits and beyond.

The developed model was validated using experimental data from literature.<sup>19,20,22–25</sup> The corresponding validation studies can be found in Supporting Information: Appendix A.

## 2.2 | Musculoskeletal simulation

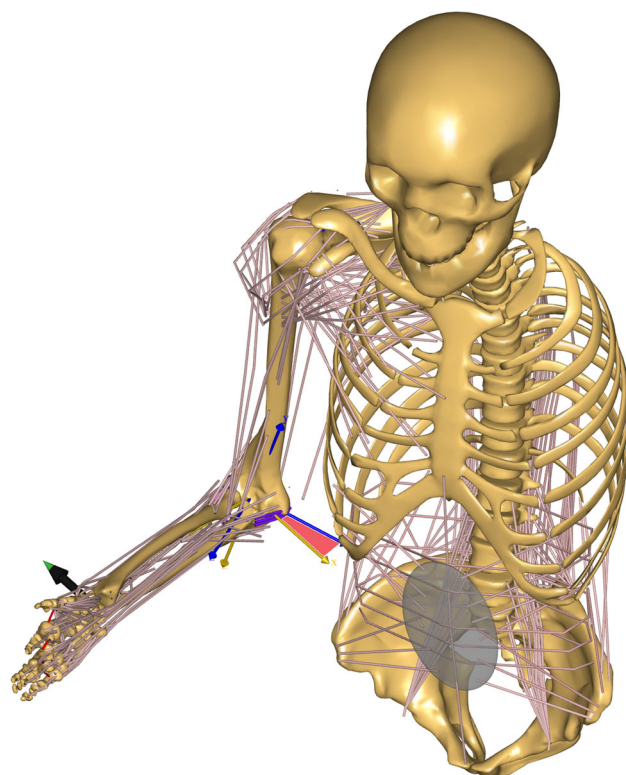
For the performed simulations both legs and the left arm were omitted and the model was scaled using the default human model (50th percentile male anthropometrics) with a height of 1.75 m (and a corresponding upper arm length of 34.0 cm/forearm length of 26.9 cm) and a body mass of 75 kg.

To investigate the stability of the elbow under the conditions of varus and valgus moments, the elbow was subjected to a corresponding force at the ulnar end in the neutral position of the hand. These moments were applied under 0°, 45°, and 90° flexion

while the respective cubital angle was analyzed. The graphical interface of the simulation is shown in Figure 1.

In close collaboration with experienced practicing physicians, various scenarios of ligament injuries, muscle, and bone structures damages that occur in everyday clinical practice were identified. Traumatic elbow instability derives in most cases from elbow dislocation and involves the primary stabilizers (see introduction) or a combination thereof. In addition secondary stabilizers and muscles may also be involved in the injury. Some of the initially secondary stabilizers become primary stabilizers in cases of elbow dislocation scenarios. The resulting scenarios, which were investigated in this study using musculoskeletal simulation models, are summarized in Table 1, and represented the most commonly involved primary stabilizers as well as the most commonly involved combinations of injuries.

For the realization of each scenario, the stiffness of the corresponding ligaments or the maximum muscle forces of the extensor/flexor muscles were set to zero, respectively. The fracture of the radial head was accomplished by adjusting the torsion spring present in the elbow joint according to the data of Morrey,<sup>22</sup> in which the radial head was excised.



**FIGURE 1** Graphical interface of the AMS simulation regarding the elbow stability testing. In this illustration, the stability testing under 90° flexion and application of a valgus force is shown (black arrow). The blue coordinate system is the reference frame of the elbow joint on the humerus and the yellow coordinate system is the corresponding frame on the ulna. The rotation of these coordinate systems corresponds to the cubital angle (red marked area). AMS, AnyBody Modeling System.

**TABLE 1** Overview of the nine scenarios, with “x” indicating which of the injuries are included—lateral ligament rupture (LL), radial head fracture (RH), posterior medial ligament rupture (ML-P), complete medial ligament rupture (ML), finger and wrist extensor muscle tear-off (EM), and finger and wrist flexor muscle tear-off (FM)

	LL	RH	ML-P	ML	EM	FM
Scenario 1	x					
Scenario 2	x	x				
Scenario 3	x	x			x	
Scenario 4			x			
Scenario 5				x		
Scenario 6				x		x
Scenario 7	x	x	x			
Scenario 8	x	x		x		
Scenario 9		x				

## 2.3 | Data analysis

A total of 5.790 calculated models provide the basis for data analysis of this study. For each flexion angle, 10 different parameter studies (intact case + nine scenarios according to Table 1) were performed; each with 193 simulation models, whereby the valgus-varus moments for each parameter study varied between 6 Nm in valgus and varus direction ( $\pm 0.0625$  Nm between two simulations). For data analysis, the stability contribution to low (2 Nm) and high (4 Nm) moments of each scenario was calculated according to Frangiamore et al.<sup>26</sup> for the three investigated flexion angles (0°, 45°, and 90°).

For the intact case, the cubital angle was determined for 2 Nm ( $\theta_{low}$ ) and 4 Nm ( $\theta_{high}$ ) (based on the range of applied moments in the study of Morrey<sup>22</sup>) and subsequently, the moment required for the individual scenarios to cause the same change in the cubital angle was analyzed.

With the collected data the determination of the stability contribution (StabCon) to low (2 Nm) and high (4 Nm) valgus and varus moments for the individual scenarios was determined according to the following formula

$$\text{StabCon} = \frac{\text{appliedmoment} - \text{requiredmoment}}{\text{appliedmoment}} \quad (1)$$

Where *applied moment* is 2 Nm (respectively, 4 Nm) for low (respectively high) varus/valgus moment, and *required moment* is the moment that causes the same cubital angle  $\theta_{low}$  (respectively,  $\theta_{high}$ ) as the intact case for each scenario. A stability contribution of a scenario of 0% would thus mean that the damaged structures do not add any value to the stability and therefore, despite the injury, 2 Nm (respectively, 4 Nm) were required to reach the cubital angle  $\theta_{low}$  (respectively,  $\theta_{high}$ ), as in the intact case. Similarly, a stability contribution of 50% means that 1 Nm (respectively, 2 Nm) is required to reach the cubital angle  $\theta_{low}$  (respectively,  $\theta_{high}$ ).

The data calculated in Equation 1 were then used to evaluate the stability of the elbow joint under conditions of valgus and varus moments.

## 2.4 | Conducted survey

A survey was conducted among a total of 19 physicians, who were asked to evaluate the individual scenarios from Table 1 (in a randomized order) according to their stability. The basis for the evaluation was the Mayo Elbow Performance Score (MEPS) according to Broberg and Morrey,<sup>27</sup> which is commonly used among professionals. In this context, stability is assessed in three sub-classes and assigned a corresponding score (gross instability (0), moderate instability (5), and stable (10)).

## 3 | RESULTS

Figure 2 show the stability contribution of the respective scenarios to varus and valgus moments (low and high) for the flexion angles of 0°, 45°, and 90° degrees. The higher the contribution for the particular scenario, the more unstable the elbow joint becomes when the respective injury occurs. An overview of which scenario represents which specific injury can be found in Table 1.

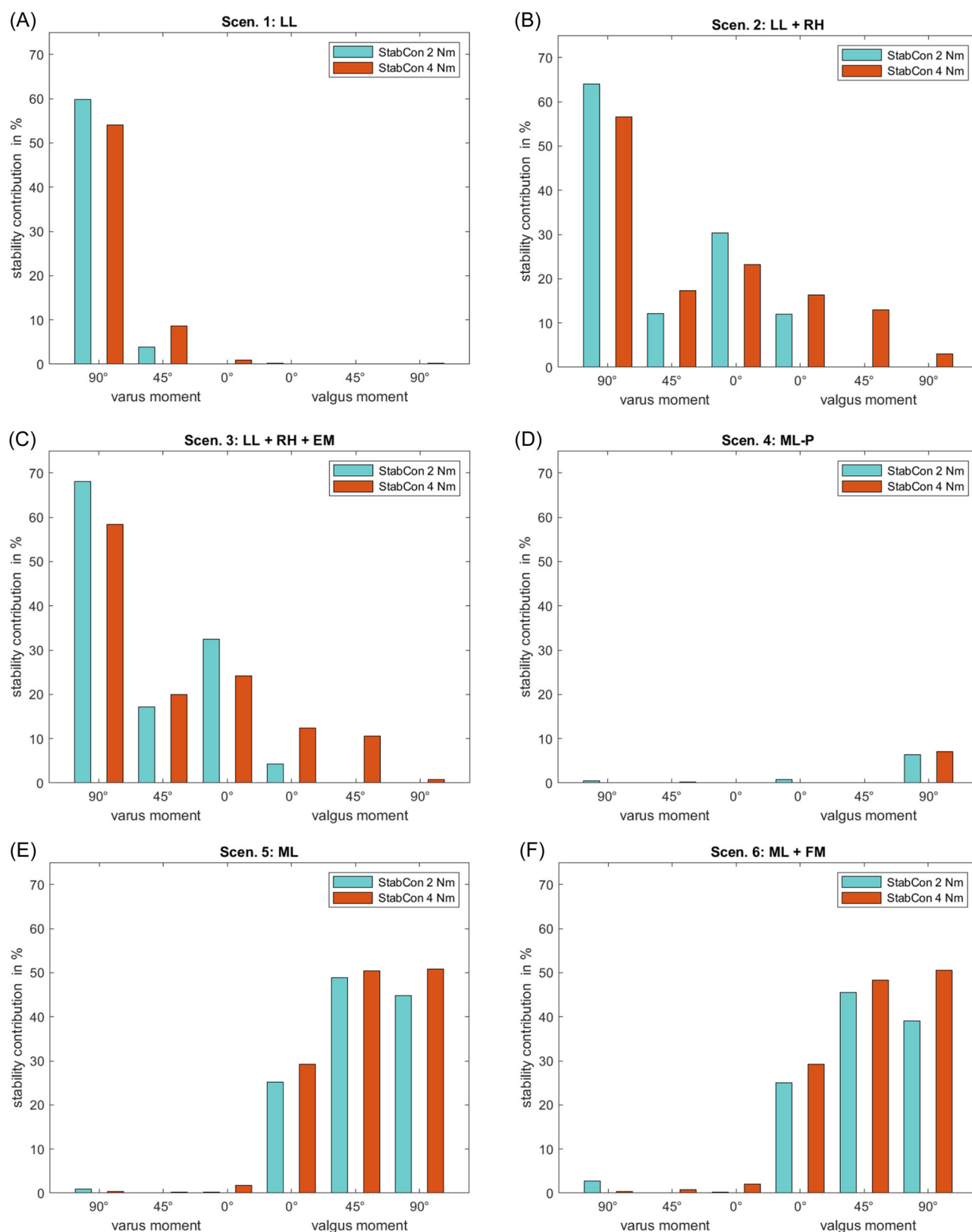
In this context, it should be noted that the stability contribution can range up to 72.8% in individual cases (scenario 7 for 90° flexion). While certain injuries (such as those occurring in scenario 5 and 6) affect elbow stability only at moments in certain directions (valgus moment in this case), other injury patterns affect the stability against valgus and varus moments, such as scenario 2, 3, and 7 under high moments, as well as scenario 8 under low and high moments. Furthermore, there exist also injury patterns whose influence on stability depends more on the respective flexion angle (scenario 1) than those of others.

Considering the contribution to elbow stability across all three flexion angles for varus and valgus moments, it can be observed that on average the respective scenario contributes to the joint stability according to Table 2.

## 3.1 | Survey among professionals

A total of 19 (3 female and 16 male) specialists participated in the survey. The average age of the participants was 39.8 ( $\pm 8.8$  SD) with an average professional experience as a practicing surgeon of 12.2 ( $\pm 7.4$  SD) years. Table 2 contains the median and average MEPS score ( $\pm$ SD) of the respective scenarios in ranked order from a MEPS score of 10 to 0. According to the median, the elbow stability of the different scenarios can be evaluated as stable (intact and scenario 9), moderate unstable (scenario 1, 2, 4, 5, 6, and 7) and grossly unstable (scenario 3 and 8).

Considering the Fleiss kappa  $\kappa$ , which determines the inter-rater stability between several raters,<sup>28</sup> the Fleiss kappa based on the survey is 0.39, which reflects a fair agreement ( $\kappa < 0$  poor,  $\kappa \in [0.0, 0.2]$



**FIGURE 2** Comparison of the change in elbow stability contribution regarding low (2 Nm) and high (4 Nm) valgus and varus moments of the different ligaments, muscles, and bony structures with respect to the particular scenarios, which include a composition of the following injuries: lateral ligament failure (LL), radial head fracture (RH), posterior medial ligament failure (ML-P), complete medial ligament failure (ML), extensor muscle failure (EM), and flexor muscle failure (FM). The subfigures contain the following scenarios of failures/injuries: (A) LL, (B) LL and RH, (C) LL, RH, and EM, (D) M-LP, (E) ML, (F) ML and FM, (G) LL, RH, and M-LP, (H) LL, RH, and ML, (I) RH.

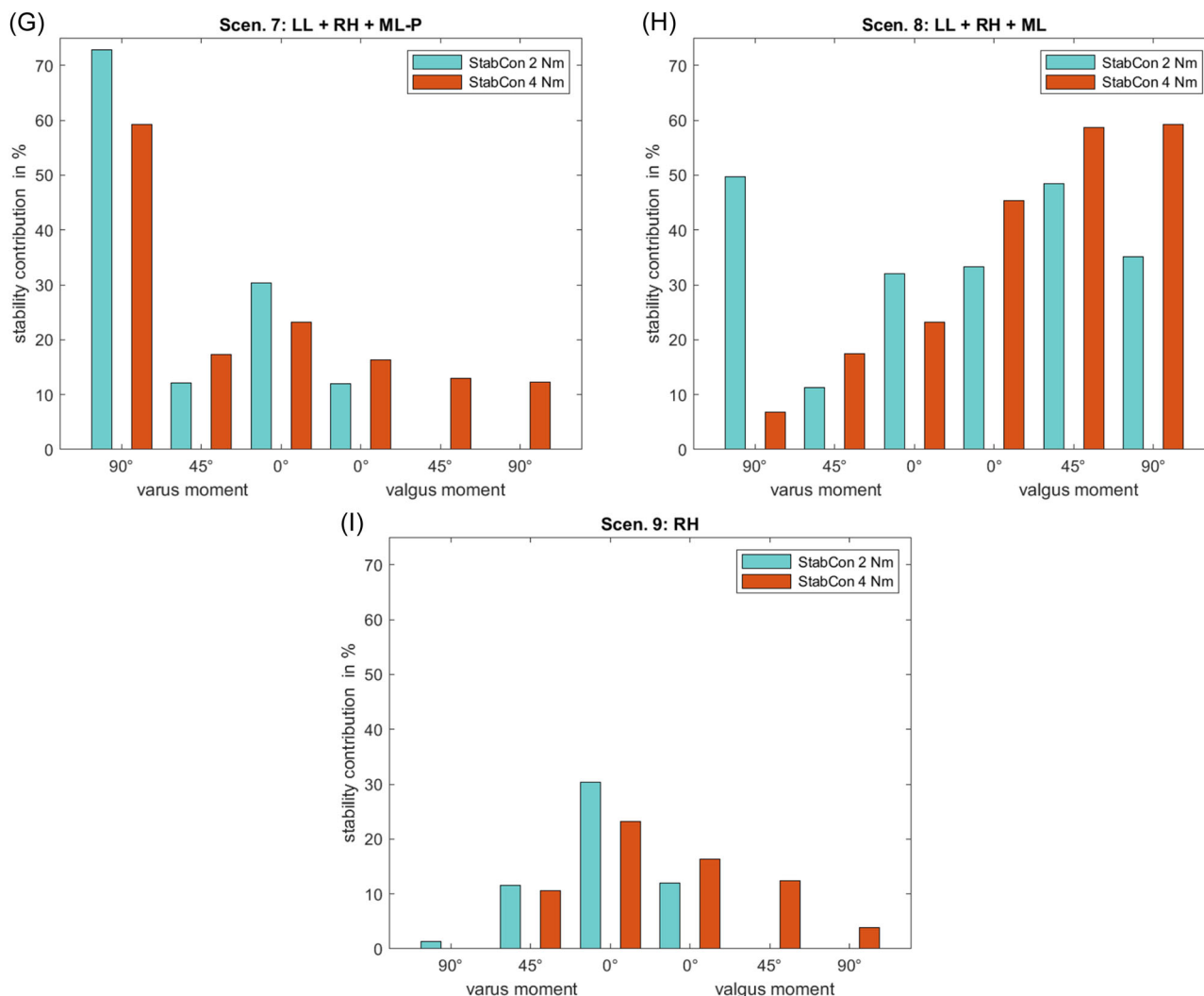


FIGURE 2 Continued

slight,  $\kappa \in [0.2, 0.4]$  fair,  $\kappa \in [0.4, 0.6]$  moderate,  $\kappa \in [0.6, 0.8]$  substantial and  $\kappa \in [0.8, 1.0]$  almost perfect agreement).

## 4 | DISCUSSION

The purpose of this study was to evaluate elbow stability to varus and valgus moments based on the calculations of a musculoskeletal model. Therefore, the deflection of the cubital angle under the effect of 2 and 4 Nm valgus and varus moments was considered and the biomechanical effects of different injury patterns on elbow stability were determined. Different contribution behaviors to elbow stability are revealed depending on the failure of different stabilizers, which allows for the derivation of appropriate treatment procedures. Based on the numerical outcome, a comparison with the clinical experience of practicing physicians is made.

As far as the musculoskeletal model is concerned, the elbow model could only be used to evaluate elbow stability in the neutral

position of the hand, and it was not possible to perform a corresponding investigation for supination/pronation (see Supporting Information: Appendix A). However, since according to Safran et al.<sup>13</sup> the elbow exhibits a maximum laxity throughout the elbow flexion during the position of the forearm in the neutral position, the chosen approach is also the most relevant one. Another limitation of the musculoskeletal simulation represents the fact that the fracture of the radial head is only based on the adaptation of the torsion spring implemented in the elbow model based on data from the study by Morrey<sup>22</sup> in which the radial head was excised.

Moreover, it should be mentioned that the cubital angle is usually more pronounced in women than in men. According to the data of van Roy et al.<sup>24</sup> the cubital angle between women and men differs mainly at a flexion angle of 0° to about 40°. Beyond that, these differences accommodate each other. The flexion angle of the model is also within the standard deviation of both the men and the women cohort of van Roy et al.<sup>24</sup> from a flexion angle of 30° (see Supporting Information: Appendix A7). If there would be a deviation between women and men, it



**TABLE 2** The MEPS score ( $\pm$ SD) of the investigated scenarios according to the conducted survey among 19 physicians and average contribution of every scenario according to the musculoskeletal simulations

	median MEPS score	average MEPS score	( $\pm$ SD)	sim. average contribution (%)
Intact	10	10.0	0.0	-
Scenario 9	10	8.7	2.3	10.1
Scenario 4	5	6.8	3.0	1.3
Scenario 1	5	6.3	2.3	10.6
Scenario 2	5	5.0	2.9	20.7
Scenario 5	5	5.0	0.0	21.1
Scenario 7	5	3.2	2.5	22.4
Scenario 6	5	2.9	2.5	20.3
Scenario 3	0	2.1	2.5	20.7
Scenario 8	0	1.3	2.8	35.0

Note: The different scenarios are ranked according to their MEPS score. Abbreviations: MEPS, Mayo Elbow Performance Score; SD, standard deviation.

would be in the extension. At higher cubital angles, the medial ligaments are slightly more preloaded and thus in scenario 5–8 the contribution to instability would likely increase slightly more. However, this statement is also difficult to make from the point of view that the cadaver studies on which the presented model is based did not distinguish between male and female specimens.

Also, the fact that the model is based on biomechanical data derived from older specimens limits the model's quantitative power. In younger patients, the ligament stiffnesses would be higher, so that a smaller cubital angle would presumably be shown with a valgus varus moment of 2 Nm (respectively, 4 Nm). However, the qualitative description of the contribution of elbow stability remains the same under the assumption of a lateral and medial constant decrease in ligament stiffness with age.

Furthermore, the outcomes based on the numerical simulation in this study are restricted to expected varus and valgus loads as they might appear during activities of daily living or sports. In these cases, muscles are capable of compensating some of the loads and therefore protect the passive structures. However, the muscle model used for the simulation does not take into account the passive structure of the muscles that serve as stabilizers in the stability of the elbow joint.<sup>8</sup> To be able to represent these passive structures, the muscle model according to Hill would have to be considered,<sup>29</sup> but important parameters for the muscles of the upper extremity are still missing within the AMS. A future stability study based on a muscle model according to Hill, could therefore provide further insights.

Moreover, it is important to keep in mind that the AMS always assumes trained movements when determining the individual muscle forces and optimizes them accordingly. By changing the basic input parameters of the numerical simulation (as it is

the case in the simulation of the different scenarios), the muscles are recruited in a different order. To ensure that the occurring change in stability contribution is caused by the injuries specified in the respective scenario and not by a change in muscle recruitment, the muscle activities must be considered accordingly. If we consider the change in muscle activity of the upper extremity between the individual scenarios for one and the same muscle, a maximum deviation of 4.9% (m. deltoideus) for 0° flexion, 7.0% (m. pectoralis major) for 45° flexion, and 10.9% (m. brachialis) for 90° flexion can be determined. While the first two are less relevant for elbow stability in terms of the size change and the muscle concerned, this is certainly the case for 90° flexion. The m. brachialis shows very little to no activity in all cases except in scenario 8 under a 4 Nm varus moment where the activity is 10.9%. The resulting stabilization of the elbow joint by the m. brachialis may thus be the reason for the relatively low stability contribution of scenario 8 in Figure 2H.

The presented results of this study allow detailed observations of different luxation patterns and their effects on elbow stability. The advantage of the elbow assessment based on musculoskeletal simulation is the investigation of the influence of different failure combinations of primary and secondary stabilizers. Nevertheless, in the context of this study, the failure of individual stabilizers was simulated as well. These outcomes can therefore be compared with the results of previous studies. According to Callaway et al.,<sup>30</sup> the failure of the posterior part of the medial ligament (scenario 4) has no effect on the valgus stability; only in the case of a section of the total medial ligament (scenario 5) a significant valgus stability can be observed. The entire MCL contributes approximately one-third in extension and half in 90° flexion to elbow stability.<sup>4</sup> No significant valgus instability is observed after resection of the radial head (scenario 9); this only occurs if the medial ligament is also damaged (scenario 8).<sup>4</sup> The simulation model accurately reproduced all these points.

Looking at the different combinations of the failures of the respective primary and secondary stabilizers, it can be seen that the structures responsible for the stability against varus moments show a slightly higher contribution to the elbow stability against low occurring moments than high occurring moments; in the case of valgus stability, however, this pattern is reversed. Furthermore, it is notable that certain injury patterns, for the most part, only affect stability to varus (scenario 1) and valgus (scenario 5 and 6) moments, whereas others provide instability to all moments (scenario 7, 8, and 9).

While the comparison of the evaluation of elbow stability with that from the survey yields many parallels, some differences must be noted. For example, scenario 8 is the most unstable injury in both cases (average MEPS score 1.3; average stability contribution 35.0%), and scenarios 1 (average MEPS score 6.3; average stability contribution 10.6%), 4 (average MEPS score 6.8; average stability contribution 1.3%) and 9 (average MEPS score 8.7; average stability contribution 10.1%) the most stable. Only scenario 3, which has an average MEPS score of 2.1, shows an average stability contribution of 20.7%, which is comparable to scenarios 2, 5, and 6. However, the survey conducted with only 19 practicing

physicians is not representative enough for a general statement. In addition, it is difficult to reduce such a highly complex topic as the assessment of elbow stability to an ordinal scale with only three values (gross instability [0], moderate instability [5], stable [10]). This conclusion is also supported when considering the Fleiss kappa  $\kappa$ , which determines the inter-rater stability between several raters.<sup>28</sup> The Fleiss kappa based on the survey is 0.39, which reflects a fair agreement. Accordingly, a conclusion can be drawn that even among the surveyed physicians there was not always unanimous agreement on how to assess elbow stability. An objective basis for evaluation, as represented by the results from musculoskeletal simulations, can thus support physicians in such assessments in the future. Especially since detailed and objective stability evaluations are possible from the observations of Figure 2. From this stability analysis, appropriate rehabilitation interventions/exercises can be derived for the respective injury.

## 5 | CONCLUSION

The study presented a numerical determination of elbow stability against varus and valgus moments with regard to clinical injury patterns, as well as a comparison of the numerical outcome with experience gained in clinical practice. The numerical predictions agree well with the assessments of the clinical specialists and differ slightly only in individual cases. Thus, the results from musculoskeletal simulation can make an important contribution to a more objective assessment of elbow stability. In further steps, the model could be extended to include supination and pronation, and therefore could be used to simulate specific injuries (like partial ruptures of certain ligaments) of individual patients and to derive individualized rehabilitation interventions based on the results.

## AUTHOR CONTRIBUTIONS

Maximilian Melzner and Franz Süß designed and performed the numerical simulations and the analytic calculations. This was done in constant exchange with Christian Pfeifer, who supported the simulation part with his clinical expertise. Christian Pfeifer and Sebastian Dendorfer supervised the whole project, aided in interpreting the results and worked on the manuscript. All authors provided critical feedback and helped shape the research, analysis and manuscript.

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## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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