Movement control in patients with shoulder instability: a comparison between patients after open surgery and nonoperated patients

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Background: Open surgery to correct shoulder instability is deemed to facilitate recovery of static and dynamic motor functions. Postoperative assessments focus primarily on static outcomes (e.g., repositioning accuracy). We introduce kinematic measures of arm smoothness to assess shoulder patients after open surgery and compare them with nonoperated patients. Performance among both groups of patients was hypothesized to differ. Postsurgery patients were expected to match healthy controls.

Methods: All participants performed pointing movements with the affected/dominant arm fully extended at fast, preferred, and slow speeds (36 trials per subject). Kinematic data were collected (100 Hz, 3 seconds), and mixed-design analyses of variance (group, speed) were performed with movement time, movement amplitude, acceleration time, and model-observed similarities as dependent variables. Nonparametric tests were performed for number of velocity peaks.

Results: Nonoperated and postsurgery patients showed similarities at preferred and faster movement speeds but not at slower speed. Postsurgery patients were closer to maximally smoothed motion and differed from healthy controls mainly during slow arm movements (closer to maximal smoothness, larger movement amplitude, shorter movement time, and lower number of peaks; i.e., less movement fragmentation).

Conclusions: Arm kinematic analyses suggest that open surgery stabilizes the shoulder but does not necessarily restore normal movement quality. Patients with recurrent anterior shoulder instability (RASI) seem to implement a “safe” but nonadaptive mode of action whereby preplanned stereotypical movements may be executed without depending on feedback. Rehabilitation of RASI patients should focus on restoring feedback-based movement control. Clinical assessment of RASI patients should include higher order kinematic descriptors.
Shoulder instability is the most common cause of joint dislocation in humans, and 66.8% of all patients suffering from anterior shoulder dislocation will eventually develop recurrent anterior shoulder instability (RASI). Because this is most prevalent in young adults (second to fourth decade of life), it has a significant impact on the quality of daily living, mainly in occupational and recreational activities. Diagnosis of an unstable shoulder often relies on a patient’s history and on physical examination. The best diagnostic results have been reported with the apprehension and relocation tests, which have a sensitivity of 72% and 81%, and a specificity of 96% and 92%, respectively; other physical examinations and maneuvers have proved less accurate.

First treatment procedures of RASI are commonly nonsurgical; failure of conventional physical therapy is eventually followed by surgical intervention. Open surgery has proved reliable in stabilizing the joint. In terms of failure rate, open surgery is not significantly different from less invasive techniques, but it may expose the shoulder to higher risks of structural damage, in particular damage to structures related to the kinesthetic sense in the capsule, labrum, ligaments, and muscles. More specifically, open surgery may disrupt the sensory activity conveyed by Golgi, Ruffini, and Pacini corpuscles as well as free nerve endings, all of which provide information about joint position and muscle tension during ongoing movements. Thus, whereas open shoulder surgery may be effective in stabilizing the joint, it may cause deterioration in the control of an ongoing movement and in reproducing static positioning accuracy of the arm at the end of the movement. Yet, some authors argue otherwise and claim that shoulder surgery actually enhances the sense of arm positioning and motion by reactivating latent or uninjured neural structures underlying kinesthesia.

To explore this controversy, the current study includes measures of arm kinematics in two groups of patients with RASI. One subgroup of patients was not yet assigned to undergo surgical intervention, although patients showed signs of potential dislocation, failure to useafferent feedback, and muscle weakness. This nonoperated group was assigned to undergo conventional physical therapy for at least 3 months before a decision was made about surgical treatment. The second subgroup of patients was assigned to open surgical intervention as a last resource to stabilize the joint. All RASI patients were tested after recovering from treatment (surgery or a 3-month rehabilitation period) and compared with age-matched active controls who had no history of shoulder disease.

Selected kinematic parameters were computed to describe and to compare shoulder motion during 3-dimensional point-to-point arm movements in the different groups.

We introduced a model-based approach whose validation comes from mathematical proof. A major assumption of the proposed model is that the motor system tends to optimize movement. In the current study, maximal smoothness is assumed as the optimization constraint. In line with this approach, we assess how close subjects are (healthy or RASI patients) to scores defined by model-based kinematic parameters. Comparisons are thus in terms of “optimal” values and not in terms of “normal population” values. A second assumption that stems from a model-based approach is that arm movements are planned for the entire path, from the start to the end of the movement before execution. The system only accesses the plan and activates it in a feedforward manner. Thus, online feedback is not critical for performance, in particular during fast movements.

We hypothesized that patients who did not undergo surgical intervention and were assigned to conventional physical therapy would fail to use intrinsic feedback. It was expected that such patients would use stereotyped slower movements to avoid joint pain. Failure to use feedback would be manifested as differences in the arm movement quality compared with healthy controls.

In addition, we hypothesized that open surgery patients would not significantly differ from healthy controls; that is, they were expected to move in an unconstrained manner, presenting arm kinematic features comparable to those observed in healthy subjects.

Throughout the study, it is assumed that under the constraints of the minimum jerk model, linear motion of the elbow marker relative to the marker fixated on the acromion would correlate with the rotational motion of the shoulder joint. Smoothed arm motion in patients was assumed to reflect the intention to avoid sudden torques, unnecessary internal friction, and shoulder pain.

Materials and methods

Experimental design, participants, and procedures

This is a retrospective case-control study in which 14 healthy controls, 11 patients with RASI who had not been operated on, and 13 patients after open surgery volunteered to perform a series of point-to-point movements with the dominant/affected arm. A mixed experimental design was used to compare different...
groups (between-subject factor with 3 levels: nonoperated, postsurgery, and control). Individuals performed at different speeds (within-subject factor with repeated measures on 3 levels: slow, preferred, and fast speed of movement). Participants in the surgery group were included if they had no previous neurologic or orthopedic disorders and no documented prior surgical failure. Control subjects were included if they had no history of shoulder complaints. Descriptive data of the sample groups are shown in Table I.

### Instrumentation

After reading the instructions, participants were provided with further verbal explanations about the task and the procedures. They signed a consent form in accordance with approved procedures for human experimentation.

During the experimental trials, participants were seated on an adjustable chair such that the elbow joint was at a 90° flexion angle. The midline of the body was aligned with the center of the workspace defined over a table top; that is, a body-centered reference frame was used. Spherical reflective markers (radius = 0.5 cm) were attached by supporting exoskeletal frames to the subject’s elbow (5 cm from the elbow, aligned with the lateral epicondyle of the humerus) and shoulder (2 cm from the shoulder, on top of the upper lateral extreme of the acromion) of the affected/dominant upper limb. In the static position, the shoulder center of rotation was assumed to be 5.4 cm inferior to and 1.2 cm medial to the marker on the acromion. To calculate the instantaneous center of rotation, further data collection is required (additional external markers) and somewhat complex computations are needed to derive from the 3 Euler angles of the joint the vector of rotation of the shoulder as a function of time relative to some fixed reference-configuration. Instead, we assumed that the elbow marker would pivot relative to a shoulder marker, and this linear (although semicircular) motion was considered a first-order approximation of the ability to rotate the shoulder joint. Such a measure was deemed simple enough to detect differences in the quality of shoulder motion among the subjects who participated in our study.

The participants performed an unconstrained reaching movement back and forth with the arm fully extended from 4 starting locations (far left, left, right, and far right) to 1 target located outside hand reach above the head (at a height of approximately 150 cm from the center of the table), as illustrated in Figure 1.

After reading the instructions and signing the consent forms, participants practiced the task for 1 minute before the initiation of the data collection process. During these familiarization trials, the examiner replied to questions, provided verbal feedback about the task, and performed a routine check of the previously calibrated hardware. Each set of movements was performed at 1 of 3 speeds: preferred speed, faster than preferred speed, or slower than preferred speed. The order of the trials (targets and speeds) was randomized for each subject to prevent order effects.

Coordinate data from the passive reflective markers were sampled within the infrared spectrum at a rate of 100 Hz by 3 cameras (ProReflex MCU240, Qualysis, Gothenburg, Sweden) located at fixed locations optimized to collect marker data. All cameras were synchronized and interfaced to a computer by a 12-bit A/D converter that allowed sampling of data and further storage in a PC by use of suitable software (Qualysis Track Manager). The duration of each (back and forth) movement was required to be less than 3 seconds; occasional trials that took longer were repeated.

### Data preprocessing

Data processing was performed with use of MatLab code (v7.04, MathWorks Ltd, Natick, MA, USA). Raw marker coordinates were zeroed to estimated joint locations (from the exoskeletal support of the marker to the estimated center of joint rotation). Data were then low-pass filtered (second-order Butterworth) with a cutoff frequency of 6 Hz and zero-time lag. An automatic threshold-based algorithm was used for detection of the start and end of each movement. A gross estimate of the onset and end of the movement was initially obtained by finding the times when the tangential velocity was 10% of the peak tangential velocity. However, such values underestimate the onset time and the end time of the velocity profiles. Thus, both extremes were reconstructed using a fourth-order minimum jerk polynomial fit for extrapolation of the zero-velocity level. This procedure is common, given the sensitivity of most data collection systems, which capture also noise from different sources (optic noise, such as infrared reflections; biologic noise, such as tremor and body sway; or marker movement over the skin). Under the current experimental conditions, the optic system was sensitive to marker displacements within a mean accuracy of 0.35 mm at a distance of up to 3 m from the center of the workspace. This induced errors that were particularly visible on attempting to define actual movement onset and end times.

A rigid-body assumption was adopted, whereby the elbow marker was assumed to pivot around a fixed shoulder marker. Because shoulder rotations cannot be measured directly, shoulder motion was assumed to correlate with the motion of the marker attached to the lateral epicondyle of the humerus relative to the

<table>
<thead>
<tr>
<th>Variables</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nonoperated (N =11)</td>
</tr>
<tr>
<td>Age (years) *</td>
<td>26.1 ± 8.0</td>
</tr>
<tr>
<td>Men/women</td>
<td>8/3</td>
</tr>
<tr>
<td>Left-hand dominance</td>
<td>1</td>
</tr>
<tr>
<td>Reported number of previous dislocations *</td>
<td>9.5 ± 3.6</td>
</tr>
<tr>
<td>Subjects with atraumatic first dislocation</td>
<td>3</td>
</tr>
<tr>
<td>Physiotherapy (months)</td>
<td>3.9</td>
</tr>
</tbody>
</table>

* Nonsignificant differences between groups.
marker attached to the lateral extreme of the acromion. The resulting 3-dimensional arm displacements were differentiated to obtain the tangential velocity-time profiles from which the dependent variables were computed.

**Dependent measures and analyses**

The following dependent variables were used in the analyses.

Movement time (MT) was determined from the velocity-time curve as the difference between times of the start and end of the movement. The just noticeable difference (JND) for MT in healthy people is ≈75 ms. Therefore, differences between healthy people and patients that exceed this MT limit could be considered true perceivable differences.

Movement amplitude (MA) was calculated from the integral of the tangential velocity profile and assumed to represent the "quantity of motion" from the start to the end of the movement, regardless of the path taken. The JND for spatial detection of an error during arm movements in healthy people is about 1.5 cm. Values below the JND cannot be perceived and may be attributed to noise rather than to real differences between healthy people and shoulder patients.

Duration of the arm acceleration phase (AT) was computed as the percentage of time accelerating the arm relative to MT, that is, from movement onset to peak velocity. According to the model predictions, the AT phase should take 50% of MT. This outcome measure provides information about the temporal symmetry of the velocity profile.

A similarity index (SI) was computed as a measure of the differences between a simulated maximal smoothness profile and the observed tangential velocity profiles. This measure was based on the difference between the area covered by the minimum-jerk model profile and the area covered by the observed tangential velocity profile. For such a modeled-observed comparison, the number of samples in the simulated and experimental data was equated by resampling both modeled and real velocity-time curves at 1000 Hz using cubic-spline interpolation and then resampling both back at 100 Hz. Modeled-observed difference closer to zero meant that the maximal smoothness constraint was more closely followed.

The number of peaks (NP) in the tangential velocity profile was used as a measure of movement fragmentation. The first time-derivative of the tangential velocity profile (i.e., the acceleration-time curve) was obtained. The number of zero crossings was then detected, where each zero crossing signifies that the velocity profile reached a peak. By definition, smooth motion should not be fragmented, and therefore only 1 zero crossing should be expected in the acceleration-time curve for maximally smooth movements. Spurious peaks detected by the algorithm were disregarded if they were equal to or shorter than 5 samples and if their relative amplitude was less than 10% of the peak tangential velocity.

The schematic illustrations in Figure 2 visualize previous definitions and detection points for the different variables derived from the tangential velocity profiles.

Effects of the group (A, nonoperated; B, postsurgery; C, controls) and speed factors (S, slow; P, preferred; F, fast) were assessed for the different variables (MT, MA, AT, and SI) using multiple 2-way analyses of variance (ANOVAs) with repeated measures on speed.

Number of peaks (NP) does not fit a gaussian (normal) distribution because the chance of occurrence of 1 peak in the velocity profile is inherently higher than 2, and the chance of having 2 peaks is higher than 3 peaks of velocity, and so on. In addition, speed of movement is a main covariate of number of velocity peaks because at a fast speed compared with a slow speed of movement, the chance of having a unimodal (single-peak) profile increases. Similarly, the chance of having a larger number of peaks increases with long movement durations. Considering the previous issues, NP was likely to fit a Poisson distribution. Therefore, nonparametric \( \chi^2 \) (Chi square) was used for NP analyses.

The JMP-5.1 package (SAS software, Cary, NC, USA) was used for all statistical analyses; the significance level was set at \( P \leq .05 \).

**Results**

Descriptive data for the different outcome measures are presented in Table I. In light of the preceding section, if
small but significant statistical differences are detected (e.g., for movement time and movement amplitude), such differences are not likely to be perceived by the individuals if they fall below JND values reported in the literature. In addition, the variance may differ among different groups, although absolute differences may be small. For instance, our results show that the variance particularly for temporal measures (SD values, Table II) tended to be smaller for patients compared with healthy controls, whereas amplitude of movement was more variable in patients after

Table II

<table>
<thead>
<tr>
<th>Variables</th>
<th>Speed</th>
<th>A, Nonoperated</th>
<th>B, Postsurgery</th>
<th>C, Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>MT (s)</td>
<td>Slower</td>
<td>1.11 ± 0.15</td>
<td>1.03 ± 0.17</td>
<td>1.18 ± 0.19</td>
</tr>
<tr>
<td></td>
<td>Preferred</td>
<td>0.96 ± 0.12</td>
<td>0.89 ± 0.11</td>
<td>1.00 ± 0.19</td>
</tr>
<tr>
<td></td>
<td>Faster</td>
<td>0.81 ± 0.12</td>
<td>0.76 ± 0.12</td>
<td>0.78 ± 0.12</td>
</tr>
<tr>
<td>MA (m)</td>
<td>Slower</td>
<td>0.32 ± 0.07</td>
<td>0.30 ± 0.07</td>
<td>0.28 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>Preferred</td>
<td>0.31 ± 0.08</td>
<td>0.30 ± 0.08</td>
<td>0.28 ± 0.07</td>
</tr>
<tr>
<td></td>
<td>Faster</td>
<td>0.31 ± 0.09</td>
<td>0.30 ± 0.08</td>
<td>0.26 ± 0.08</td>
</tr>
<tr>
<td>AT (% of MT)</td>
<td>Slower</td>
<td>48.9 ± 6.6</td>
<td>49.2 ± 5.9</td>
<td>46.8 ± 5.5</td>
</tr>
<tr>
<td></td>
<td>Preferred</td>
<td>50.4 ± 5.1</td>
<td>50.4 ± 5.6</td>
<td>46.9 ± 5.7</td>
</tr>
<tr>
<td></td>
<td>Faster</td>
<td>51.1 ± 5.6</td>
<td>50.1 ± 5.4</td>
<td>48.4 ± 6.3</td>
</tr>
<tr>
<td>SI (NU; 0 = no diff.)</td>
<td>Slower</td>
<td>0.09 ± 0.04</td>
<td>0.07 ± 0.03</td>
<td>0.09 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>Preferred</td>
<td>0.07 ± 0.04</td>
<td>0.07 ± 0.04</td>
<td>0.08 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>Faster</td>
<td>0.07 ± 0.04</td>
<td>0.08 ± 0.04</td>
<td>0.08 ± 0.04</td>
</tr>
</tbody>
</table>

MT, movement time; MA, movement amplitude; AT, acceleration time; SI, similarity index; NU, normalized units.
surgery regardless of speed of movement. As expected, variability also tended to decrease for all groups and measures at faster than preferred arm movement speed (see tangential velocity profiles in Fig. 3).

The profiles in Figure 3 depict the effect of speed of movement on variability, where lower path variability could be attributed to moving faster. Unexpectedly, nonoperated patients and postsurgery patients moved faster than healthy controls (shorter MT for similar MA), whereas movement durations were more variable in nonoperated patients compared with patients after surgery. This was particularly noticeable at the preferred speed of movement and suggests that surgery for shoulder joint stabilization may induce changes (perhaps limitations) in arm motion. The following statistical analyses confirm the observations made on individual examples depicted in Figure 3.

The analysis on NP shown in Table III presents the probability of occurrence of 1 to 5 peaks in the arm velocity profiles of healthy controls, nonoperated patients, and patients after surgery.

A higher chance of generating unimodal profiles was observed when moving faster for all individuals as expected. This may suggest that arm movements in different subjects share invariant features that closely follow a maximal smoothness constraint (see also examples in Fig. 3, panels on the right). However, unimodal profiles were also observed at slower speeds of movement for both groups of patients and not as much in healthy participants. Thus, differential effects among groups are more likely to be observed at preferred and slower than preferred speeds of movement. This effect is more pronounced for patients after open surgery compared with patients who did not undergo surgery.

ANOVA results presented in Table IV show significant group effects for all dependent variables. This major effect could be attributed to the arm movements of postsurgery patients who, in contrast to our hypothesis, were significantly different from controls. Postsurgery patients presented shorter MT but larger MA (i.e., faster movements) compared with both nonoperated patients and healthy controls. They followed more closely (smaller SI) the modeled minimum-jerk velocity profile and spent nearly 50% of the movement time in the acceleration phase as also predicted by the model (closer to the model than controls but not different from nonoperated patients).

Differences attributed to patients after surgery were enhanced when movements were performed at slower than preferred speeds, as shown by the significant differences found by Tukey HSD post hoc pair-wise comparisons. The ANOVA effects are illustrated in Figure 4.
Finally, postsurgery patients showed a lower probability of generating multiple peaks in the velocity profiles (less fragmentation) compared with controls. They were equally likely to perform movements with a single velocity peak and less likely to have 2, 3, or 4 peaks compared with either controls or nonoperated patients (Table III). χ² analysis carried out on NP confirmed the group effect (bottom, Table IV) and together with the results shown in Table III suggests that the group effects can be attributed primarily to differences in the way patients perform after being treated with open surgery to correct shoulder instability.

### Table III

<table>
<thead>
<tr>
<th>Number of peaks</th>
<th>Speed</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A, Nonoperated</td>
</tr>
<tr>
<td>One peak (%)</td>
<td>Slower</td>
<td>55.75</td>
</tr>
<tr>
<td></td>
<td>Preferred</td>
<td>70.18</td>
</tr>
<tr>
<td></td>
<td>Faster</td>
<td>82.30</td>
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<tr>
<td>Two peaks (%)</td>
<td>Slower</td>
<td>31.86</td>
</tr>
<tr>
<td></td>
<td>Preferred</td>
<td>24.56</td>
</tr>
<tr>
<td></td>
<td>Faster</td>
<td>16.81</td>
</tr>
<tr>
<td>Three peaks (%)</td>
<td>Slower</td>
<td>10.62</td>
</tr>
<tr>
<td></td>
<td>Preferred</td>
<td>4.39</td>
</tr>
<tr>
<td></td>
<td>Faster</td>
<td>0.89</td>
</tr>
<tr>
<td>Four peaks (%)</td>
<td>Slow</td>
<td>1.77</td>
</tr>
<tr>
<td></td>
<td>Preferred</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>Faster</td>
<td>—</td>
</tr>
<tr>
<td>Five peaks (%)</td>
<td>Slower</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Preferred</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Faster</td>
<td>—</td>
</tr>
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</table>

### Table IV

<table>
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<tr>
<th>Variables</th>
<th>Effects</th>
<th>Speed</th>
<th>Interactions</th>
<th>*Tukey HSD post hoc</th>
</tr>
</thead>
</table>
| MT (s)    | $F = 41.97; P < .0001$ | $F = 465.45; P < .0001$ | $F = 8.31; P < .0001$ | Speed $S > P > F$
|           |         |       |              | Group $B < A < C$
|           |         |       |              | Group $\times$ Speed $Fast, A = B = C$
|           |         |       |              | Preferred, $A > B, A = C$
|           |         |       |              | Slow, $B < A < C$
| MA (m)    | $F = 30.17; P < .0001$ | $F = 2.55; P = .0784$ | $F = 1.090; P = .3650$ | Speed $S = P < F$
|           |         |       |              | Group $A > B > C$
| AT (% of MT) | $F = 28.55; P < .0001$ | $F = 7.084; P = .0009$ | $F = 1.1090; P = .351$ | Speed $S < F = P$
|           |         |       |              | Group $A > B > C$
| SI (NU)   | $F = 3.705; P < .0249$ | $F = 6.436; P < .0017$ | $F = 2.092; P < .0798$ | Speed $S > P, P = F$
|           |         |       |              | Group $A = B, B > C$
| NP (counts) | $\chi^2 = 6.696; P = .0352$ | $\chi^2 = 50.12; P < .0001$ | $\chi^2 = 5.457; P = .2435$ | Speed $S = P > F$
|           |         |       |              | Group $B > A, A = C$ |

Two-way mixed-design ANOVAs (speeds [slow, preferred, fast], groups [A, nonoperated; B, postsurgery; C, healthy control]) when movement time (MT), movement amplitude (MA), acceleration time (AT), and similarity index (SI) were used as dependent variables. *The significance level for all post hoc differences was set at $P \leq .05$. Number of peaks in the velocity profile (NP) was analyzed by $\chi^2$. 

### Discussion

A lack of universal outcome measures seems to be a major drawback in the assessment of arm function in shoulder patients. Most diagnoses are based on verbal reports about symptoms of instability and recurrent incidents. Some add common performance tests limited to static postures where the outcome measure is the error after repositioning the arm at a final location. Kinematic features representing qualitative aspects of arm movement have been overlooked. Thus, we adopted a parameterization of movement derived
from a maximal smoothness model (i.e., the minimum-jerk model). We assumed that such a model would describe qualitative aspects of movement and that smoothness could be used as a clinical marker for objective assessment of arm function in patients with RASI.

For our purposes, we focused on spatial and temporal kinematic features. The tangential velocity profile of the arm was of particular interest. More specifically, potential measures of movement quality were derived from a maximal smoothness assumption. Smoothness of movement describes the evolution of the movement over time, and it is an aspect as yet unexplored in the assessment of orthopedic patients. We calculated several parameters that originate in a minimum jerk description as previously used in neurologic patients.27,30

Arm performance of nonoperated RASI patients was expected to differ in terms of path smoothness from performance of patients after open shoulder surgery for joint stabilization and from performance of healthy controls. The postsurgery group was not expected to differ from healthy counterparts, particularly considering that the literature reports full recovery of arm function and shoulder joint stability after open surgery.32 Open surgery was also expected to restore the sense of joint positioning.23,43,47

Our analyses, however, showed a different reality, and as far as the quality of the movement is concerned, similarities were observed between nonoperated patients and patients after shoulder surgery. One possibility is that the kinematic parameters were not sensitive enough to differentiate between these two groups of patients. Should this be the case, existing differences in arm kinematics compared with healthy controls would have not reached any significance either. However, this was not the case. Thus, another interpretation was suggested on the basis of motor control strategies adopted by patients compared with healthy participants.

In several respects, the analyses showed that the kinematic features of nonoperated patients and patients after

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**Figure 4** The subplots depict the results of the mixed-design ANOVAs (left to right: effects of group, speed, and group × speed interactions) for 4 variables (top to bottom: MT, movement time; MA, movement amplitude; AT, acceleration time; and SI, similarity index).
surgery were closer to the model predictions. That is, patients more closely followed the maximal smoothness criterion than healthy controls did. Furthermore, this trend was more evident while moving slower compared with preferred or faster speeds of movement, which is counterintuitive since healthy people are expected to outperform patients in all cases (i.e., they should perform smoother arm movements). However, a more careful look into the results provides support for an alternative interpretation.

Our results suggest that joint stability is achieved after open surgical intervention although increased stability may come at the expense of a reduction in quality of movement. We further argue that shoulder patients do not use the same movement strategy to reach with their arm. Normally, healthy motion is adaptable, with paths and speeds of movement that may quickly (online) change according to ever-changing task conditions. Healthy individuals may thus regulate ongoing movements by using kinesthetic feedback for online corrections. RASI patients after surgery, on the other hand, might not rely on kinesthesia, particularly if the sensory machinery has been damaged as a consequence of the trauma.

In our study, nonoperated patients and postsurgery patients moved in a rather stereotypical manner that followed closely the maximal smoothness modeled values (even closer than healthy participants). Thus, they seemed to implement a feedforward mode of control with shorter MT for similar path lengths (see Table II) and fewer corrections (less movement fragmentation; see number of peaks in Table III); that is, movements might have been preplanned for the entire path (i.e., patients decide before acting how they should move), and in doing so, they override the need for feedback-based correction. Under such a strategy, the affected arm moves within “safe regions” of the workspace and performs at “safe speeds” to avoid pain and reduce the risk of recurrent injury.

Such a mode of control is compatible with the minimum jerk model, which is based on the assumption that the brain plans movements to be as smooth as possible, and as a byproduct of such an intention, the arm follows the shortest possible path between the start and end locations of the movement. Under the minimum-jerk constraint, tangential velocity-time curves of the endpoint (i.e., the relative elbow motion representing the shoulder rotations) follow unimodal, symmetric, and bell-shaped velocity profiles, where 50% of the movement time is spent accelerating and 50% is spent decelerating the arm. This model assumes that a motor plan is triggered and implemented in a feedforward manner. Thus, feedback (visual, proprioceptive, or other) is not required.

In reality, minimization of jerk does not preclude the use of feedback. Some authors showed that arm proprioceptive inputs can be integrated into maximally smooth arm movements. Even if very slow accurate motion depends on online feedback (more than fast motion), such movements may follow maximally smooth paths. Nonetheless, such a mode of control is more difficult and requires long practice (e.g., Tai Chi exercise protocols). Hybrid models also suggest that feedback-based control and feedforward control coexist and become integrated before and during motor execution to generate optimal motor outcomes (e.g., adopting arm postures that require minimal kinetic energy and arm paths that follow maximal smoothness).

We introduced the minimum jerk model as a basis for parameterization of movements in RASI patients and healthy people because it is intuitive and simple, and it has been widely used and validated for characterization of graceful and effective arm motor functioning. Maximally smooth movement is characteristic of well-structured motor activities that tend to be optimal (e.g., sports like gymnastics) or fast motor responses (e.g., hand withdrawal from a noxious stimulus). The resulting movement patterns are often stereotypical, less adaptive to sudden changes in movement conditions, and often observed when afferent feedback is incomplete or unavailable (see Desmurget and Grafton for a review and complementary perspectives). Furthermore, jerk minimization has been successfully used to describe arm trajectories in patients with different neural pathologic processes (Parkinson disease, idiopathic torsion dystonia, stroke). Thus, it was considered valid for the comparison of orthopedic patients and healthy controls.

From the vantage point of the present model, shoulder patients in this study performed fast and smooth movements closer to the minimum-jerk model than healthy controls did. Fragmentation of movement was somewhat reduced in patients compared with healthy subjects, perhaps because RASI patients showed a tendency to move faster (shorter durations within similar path amplitudes). The probability of movements with unimodal tangential velocity profiles was on average ≈70% after shoulder surgery (higher or lower, depending on movement speed; see Table III). The cumulative percentage of trials with more than 1 peak was generally similar in all groups, although the fact that post-surgery patients moved faster overall (see Tables II and III) may be consistent with the increased likelihood of movements with a single peak of velocity in patients after surgery. This also partially supports our suggestion that these patients implement a feedforward strategy of control based on a structured motor model driven by the intention to move as smoothly as possible (i.e., following a minimum-jerk criterion). Preplanning arm movements to be smooth would not compromise joint stability and it may avoid regions of the workspace where pain is evoked. Although such a hypothetical strategy would not require the use of feedback, it would certainly lead to less adaptation to ever-changing conditions.

Thus, whereas therapeutic recovery of function may be an important part of postoperative treatment, this may not be sufficient. Recovery should be accompanied by a change in movement strategy with a focus on a change from a feedforward mode of control to a feedback-based
mode of control. This may require re-educating the system to rely more on its intrinsic kinesthetic sense.

**Drawbacks and future research**

In this study, internal joint rotations were neither measured nor modeled. Rather, we inferred shoulder rotations from linear marker motion. Although modeled kinematic descriptors as used here may help to understand behavioral aspects of recovery, this approach cannot provide a complete picture. Future research in RASI patients should include rotation vector kinematics to describe shoulder dynamics.

A drawback of our study is that we had no control over the level and duration of the physical therapy that our patients received. All patients were referred to physical therapy by the shoulder specialist. However, we could not verify the actual therapy training on an individual basis (duration, intensity, type). This factor might have increased the variance of our rather small sample groups. In spite of the fact that we observed significant differences between groups, future studies in RASI patients should carefully control for covariates such as duration and type of the prescribed physical therapy protocols.

**Conclusions**

The current investigation shows that smoothness parameterization can be used to describe changes in the quality of motion in RASI patients. Today, diagnoses are based on questionnaires, behavioral observations, and measurement of static errors obtained in repositioning tasks. Simple linear kinematic descriptors may be sensitive enough to capture relevant clinical differences otherwise overlooked by common clinical evaluation methods. Our study shows that estimates of arm kinematics derived from a maximal smoothness description may lead to objective diagnosis and assessment of the quality of movement in RASI patients and differentiate healthy subjects from patients who were operated and those who were not. Our approach results from a tradeoff between complex mathematical parameterization of shoulder joint rotations and simple tests of function, and thus, we suggest incorporating it in the clinical assessment protocols of RASI patients.

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**References**


