B. Trial-to-trial variability

1) Size of task-space and joint-space variance: In Fig. 6A, the logarithms of task-space variances are depicted as a function of time. Consistent with our prediction, V_Z was larger by at least 2 orders of magnitude than V_{XY}. In addition, the x-y variability changed with normalized movement time, peaking at mid-movement and slightly decreasing towards the end of movement. Therefore, we focused on the times of peak speed and end of movement for the statistical analysis, as summarized in Fig. 7A.

The x-y space variance was larger at the time of peak speed than at movement end ($F_{1;1715} = 64$; $p < 0{:}001$). This is consistent with the minimum-intervention principle [23] – the error at the end of movement was more relevant for successful task performance. The variance in teleoperated movements was smaller than in freehand ($F_{1;1715} = 49$; $p < 0{:}001$), and this difference was more pronounced at the time peak speed (time-teleoperation interaction, $F_{1;1715} = 15$; $p < 0{:}001$).

Finally, the variance of experienced surgeons was statistically significantly smaller when compared to novices at the end of movement but not at the time of peak speed (time-expertise interaction, $F_{1;1715} = 39$; $p < 0{:}001$).

Interestingly, a very different picture is revealed when examining joint-space variability. The total variability in jointsspace is depicted in Fig. 6B as a function of time. There was no statistically significant effect of time ($F_{1;1715} = 0{:}27$; $p = 0{:}6$), and therefore, statistical analysis is summarized in Fig. 7B only at the end of movement. The joint-space variance of experienced surgeons was larger than of novices ($F_{1;1715} = 64$; $p < 0{:}001$), and there was no statistically significant effect of teleoperation condition ($F_{1;1715} = 0{:}66$; $p = 0{:}4$). In the freehand condition, the variances of experienced surgeons and novices were similar, but when teleoperating, their variances were shifted upward and downward, respectively (teleoperation-expertise interaction, $F_{1;1715} = 112$; $p < 0{:}001$).

2) Coordination of joint-space variance to stabilize hand movement: The logarithm of ratio of TIM and TRM variances, R_V , is depicted for both x-y and z tasks in Fig. 6C as a function of time, and summarized in Fig. 7C for the times of peak speed **and** end of movement. $R_{V_{XY}}$ was statistically

significantly larger than zero regardless of the experience of the participants, teleoperation condition, or time (upper raw of Fig. 7C). This indicates that joint-space variance was coordinated such that the horizontal (x-y plane) movement was stabilized. This stabilization was achieved by limiting the TRM variance, but allowing large TIM variance, as depicted in Fig. 8 and supported by the statistically significant effect of the manifold on ln(V_) ($F_{1;3488} = 4437$; $p < 0:001$).
Consistent with our prediction, $R_{V_{XY}}$ was much larger than R_{V_Z}. Novices did not coordinate joint-space variability to stabilize the vertical movements of their hand, as indicated by negative values of R_{V_Z}. Interestingly, R_{V_Z} of experienced surgeons was very small, but statistically significantly larger than zero, indicating some (minimal) stabilization of vertical movement even in the absence of visual feedback in this dimension. However, because it was very small, we did not further analyze the stabilization of the z task.
$R_{V_{XY}}$ of experienced surgeons was 26% larger than of novices ($F_{1;1717} = 89$; $p < 0:001$). There was no statistically significant effect of teleoperation, because novices decreased their R_V in teleoperation, but experienced surgeons increased it at the time of peak speed, and did not change it at the end of movement (teleoperation-expertise interaction, $F_{1;1717} = 6$; $p = 0:001$). The variability in the TIM in freehand movements was similar between novices and experienced surgeons, and did not change with movement progress (Fig. 8). In teleoperated movements, experienced surgeons increased variability in both manifolds, whereas novices decreased it (teleoperation-expertise interaction $F_{1;3488} = 123$; $p < 0:001$). However, the extent of these changes was larger in the TIM than TRM (teleoperation-expertise-manifold interaction $F_{1;3488} = 120$; $p < 0:001$), and resulted in the differences in R_V depicted in Fig. 6C.
3) The effect of movement direction: The dependence on movement direction was statistically significant for all variances, including: V_{XY} ($F_{7;1715} = 4$; $p < 0:001$), V_ ($F_{7;1715} = 20$; $p < 0:001$), V_{TIM} and V_{TRM} (main effect of direction $F_{7;3488} = 20$; $p < 0:001$, and direction-manifold interaction $F_{7;1715} = 3$; $p = 0:009$), and R_V ($F_{7;1717} = 3$; $p = 0:001$).

In Fig. 9, R_V, V_{TIM}, and V_{TRM}, are depicted as a function of direction. The depth of modulation of TIM and TRM variances was large, but it was smaller for R_V. In fact, the only statistically significant contrasts between R_V in different directions were between the 180_ and the 0_ and □45_ targets. The stabilization was smallest for the 180_ target.

4) Changes in trial-to-trial variability between experimental sessions: Half of the participants performed the experiment first freehand and then teleoperated, and the other half performed first teleoperated followed by a freehand session. In Fig. 10, V_{XY}, V_, and R_V at time of peak speed are presented as a function of session number. There was a statistically significant interaction between teleoperation, expertise, and order in task-space ($F_{1;1715} = 7; p = 0:01$) and jointspace ($F_{1;1715} = 72; p < 0:001$) variances, and in R_V ($F_{1;1717} = 4; p = 0:03$). However, the patterns of differences were specific to each variance.

Horizontal task-space variance (x-y plane) was smaller in teleoperated movements than in freehand regardless of the experience of the user and the order of sessions. However, the size of the difference depended on order of sessions (teleoperation-order interaction $F_{1;1715} = 22; p < 0:001$): the difference was smaller when the first session was teleoperated than when it was freehand. There was no statistically significant main effect of order of sessions on task-space variance ($F_{1;1715} = 0:82; p = 0:36$).

In contrast, joint-space variance was smaller when participants performed freehand movements first than when they started with teleoperation ($F_{1;1715} = 185; p < 0:001$). The differences between experienced surgeons and novices were substantial. Pooled across sessions, the variance of experienced surgeons who started freehand was smaller than those who teleoperated first; this difference was in the opposite direction and much smaller in novices (experience-order interaction $F_{1;1715} = 562; p < 0:001$). Novices decreased their jointspace variance in the second session regardless of which teleoperation condition they performed first. For experienced surgeons, the direction of change depended on the order: they decreased the variance after teleoperation, and increased it (but not statistically significantly) after the freehand session.

We observed similar trends in R_V – it was smaller in the second session in all expertise-order combinations except for the experienced surgeons who started freehand. Experienced surgeons and novices who performed the freehand session first had the same level of stabilization, but in the transition to teleoperation, experts had no reduction of R_V , and novices had large reduction. In the teleoperated-first group, the R_V of

experts was statistically significantly larger than of novices, but the extent of reduction in the transition between sessions was similar between experience groups. For experts, the stabilization of the teleoperated movements was higher, and reduced to a level comparable to the freehand movements of the freehandfirst group. In contrast, the stabilization of the teleoperated movements of novices was comparable to the teleoperated movements of the freehand-first group, and decreased in the transition to freehand.

5) Correlation between R_V and performance: In Fig. 11, ln(Er _ Mt) is presented as a function of R_V . There was a small but statistically significant negative correlation between this performance metric and R_V (Pearson's _ = □0:14, transformed t-test t_{893} = □4:5; p < 0:001), suggesting that large redundancy exploitation for hand trajectory stabilization is related to improved performance. However, the linear regression trend was very weak, and the R^2 = 0:02 is extremely small, suggesting that other factors influence performance to a much greater extent.

IV. DISCUSSION

A. Factors affecting joint angles variability

Experienced surgeons exploitated arm redundancy and coordinated their arm joints for hand movement stabilization of experienced surgeons more than novices, and teleoperation with the da Vinci Si Surgical System master manipulator changed the stabilization relative to freehand performance of the same task. Interestingly, the effect of teleoperation depended on the expertise of the user: for experienced surgeons, the coordination of arm joint angles when teleoperating was larger than when moving freehand, but it was smaller for novices.

The participants coordinated the trial-to-trial variance of their joint angles such that the horizontal but not vertical trajectories of their hand were stabilized. Similar stabilization of movement by coordination of arm joints was previously reported in various tasks [27], [36]–[38]. The lack of stabilization of the vertical trajectory was not surprising because participants were only provided with visual feedback about the horizontal movement of their hand-held grasper tip. Therefore, we expected the horizontal trajectories to be more stabilized compared to the vertical. In the remainder of the discussion, we address only x-y task stabilization.

Experienced surgeons stabilized task trajectory more than novices. Their task variance was smaller at the end of movement than of novices, but their joint-space variance was larger, especially in the teleoperated condition. The UCM analysis suggests that this is due to their superior exploitation of redundancy, as evident by larger variance in TIM than TRM. This is consistent with many previous reports that task variability is reduced by coordination rather than reduction of redundant effector variability [47]. The ability to exploit redundancy and structure the variance of control variables to increase TIM without deteriorating performance was recently studied in expert stone knappers [38], cello players [48], and golfers [49]. It may be related to the external focus of attention (on the effects of actions rather than body mechanics) of experts [50]. Our study is the first one to examine the structure of arm movement variability in the context of surgical expertise.

The superior exploitation of redundancy by the experienced surgeons in our study may have resulted from factors that are not necessarily related to their RAS expertise. They may have better motor skills than the general population, especially in manual tool operation. This is particularly relevant in the current study, because we used simple non-medical movements that do not reflect surgical competence. In future studies, it would be interesting to study participants without RAS experience who have varying levels of surgical expertise, and determine whether early trainees, such as residents or fellows, would exhibit redundancy exploitation that is similar to experienced surgeons in our task. Another interesting control population for such a study would be participants without medical background who are skilled in other forms of fine manual manipulation, like silversmiths, watchmakers, opticians, or microassemblers [51], [52].

An additional factor that may have contributed to the increased exploitation of redundancy by experienced surgeons is their familiarity with the surgeon console, regardless of teleoperation condition. It is possible that the experienced robotic surgeons, unlike the novices who interacted with the system for the first time, were able to increase their TIM variability because of familiarity with the ergonomic settings of the da Vinci. Furthermore, novices may have attempted to limit the redundancy in their movement if they experienced anxiety when using an expensive robotic surgical system for the first time.

The task space variance in teleoperated movements was smaller than in freehand. This might be related to the teleoperated movements being slower, as reported in details elsewhere [12]. It was previously established that the noise in the motor system is signal-dependent [53], and therefore, faster movements that require stronger muscle activations are very likely to be more variable.

The effect of teleoperation on the coordination of arm joints angles for hand movement stabilization was different between experts and novices. Novices, who were unfamiliar with the dynamics of the master manipulator, decreased the overall variability of their arm angles, but experienced surgeons increased the joint-space variability without increasing its taskspace counterpart. The R_V of novices when teleoperating was smaller than when moving freehand. This is consistent with previously reported effect of reducing the coordination of variance during initial exposure to a force field [27]: novices were not familiar with the dynamics of the da Vinci master manipulator, and therefore, had to adapt to these dynamics, resulting in reduction of R_V. However, [27] also reported that at late exposure to the force field, variance coordination was restored. This is consistent with our observation that experts showed similar R_V in freehand and teleoperated movements at movement end, and larger teleoperated R_V compared to freehand at the time of peak speed. While the effect of the dynamics of a hand-held tool on redundancy exploitation in experienced and novice users was not studied extensively, a recent study showed that adding a back-carrying load leads to increase of stabilization of body center of mass during walking [54]. Healthy adults are experienced in carrying loads during locomotion – this is another example of experienced users increasing the ratio between TIM and TRM in the presence of familiar but challenging dynamics.

The joint-space variance and R_V depended on movement direction, and the pattern of dependence was similar across teleoperation conditions and expertise groups. This suggests that it might be related to the control of arm movement rather than being a specific effect of teleoperation that a user can learn with sufficient practice, and that the ability to exploit redundancy may depend on dextrous workspace limitations.

In the analysis of within-trial variability, consistently with biomechanics, we found large variations of joint angle movement range as a function of direction, but the effects of teleoperation and expertise were minimal. In particular, the wrist angle range of experienced surgeons was not larger than that of novices, even though wrist articulation is part of the training goals in robotic surgery, and one of the advantages of RAS over standard MIS is improved dexterity due to the addition of wrist articulation. One potential reason is that we

advantage of redundancy exploitation to be revealed in more complicated tasks.

In the current experimental design, we could not explore the progress of evolution of R_V as a function of repeated training with a robotic manipulator due to experiment length limitation. However, to gain a preliminary insight into how the coordination of arm joint angles changes, we examined task and joint space variances as well as R_V as a function of session number. Interestingly, R_V was reduced in the second session of all groups except for the experienced surgeons who transitioned from freehand to teleoperated movements. This may be a result of fatigue that caused reduction of TIM variance, consistent with a similar tendency that was reported in a recent study of locomotion [54]. The participants might have attempted to mitigate these effects by choosing trajectories that involved less used muscles, similarly to the model that was suggested in [57], and reduced the TIM variance.

The effect of fatigue may be studied specifically by performing multiple repetitions of a few movements over prolonged experimental sessions. This may contribute to the understanding of the effects of the length of a surgical case on the performance of the surgeon and the ability of his motor system to respond to unpredicted situations, and may have important implications on fatigue management in clinical settings. Previous studies suggested that decreased mobility of the head and trunk [58] alongside with awkward arm movements [59] are responsible for increased fatigue in laparoscopic surgery when compared to open surgery. Ergonomic considerations are gaining attention also in RAS [60]. Future studies may reveal the importance of redundancy exploitation for mitigating fatigue effects. In addition, we did not record the position of the head, neck, and trunk of the participants, and therefore, we could not evaluate the movement of the shoulder relative to the trunk, or the movement of the trunk in space during the performance of the task. In future studies, the role of these movements in the coordination of arm joint angles variance may be explored. Studying how they are affected by teleoperation and expertise may further advance the understanding of movement coordination in RAS.

Large R_V is not by itself a goal for optimization. In face of perturbations, R_V is expected to decrease in the attempt to minimize the deteriorating effect on task performance. However, we suggest that telemanipulators and training strategies could be designed to maximize the ability of the motor system of the surgeon to exploit redundancy, and hence maximize R_V for any given situation. Further studies are needed to suggest general principles or specific guidelines for manipulator physical structure, dynamics, or control that can maximize redundancy exploitation. Preliminary insights can be inferred from this study. For example, in the design of the master manipulators we suggest that spatial degrees of freedom should not be restricted even if only a subspace is relevant to the performance of a particular task. That is, dextrous workspace should be maximized such that it allows the surgeons to exploit the natural redundancy of their arms. This opens interesting questions for future studies, such as what is the optimal degree of redundancy and whether it might be beneficial to increase it by introducing additional redundancy in the master manipulator, or how various forms of force feedback and virtual fixtures may affect redundancy exploitation. Answering these questions may advance RAS as well as the understanding of human motor control.

Our finding of larger redundancy exploitation by experienced surgeons when compared to novices in a non-clinical task opens a promising avenue for exploring redundancy exploitation in surgically relevant procedures for surgical skill assessment. If our current findings generalize to the performance of surgical procedures, this will mean that redundancy exploitation for movement stabilization is an important motor skill that is characteristic of experienced surgeons. This may allow for a development of a novel metric for skill assessment. In addition, drills that induce redundancy exploitation could be developed. If these drills are found to improve surgical outcomes, they could be incorporated in RAS training curricula.

V. CONCLUSIONS

In a study of simple non-clinical point-to-point movements, we showed for the first time that there are differences between experienced surgeons and novice users of a da Vinci Surgical System in their exploitation of arm joint angle redundancy. Experienced surgeons coordinate their arm joint angles to stabilize hand movements more than novices, and the effect of da Vinci teleoperation depends on experience – experienced surgeons increase teleoperated stabilization relative to freehand, whereas novices decrease it.

These results open a promising and exciting avenue for exploring how redundancy exploitation benefits clinical task performance, and its potential for skill assessment and surgical training optimization. Enabling redundancy exploitation may also serve as an optimization goal for the design and control of surgical manipulators. Eventually, such improvement in system design, skill assessment, and training may promote RAS by taking advantage of the flexibility of the motor control system of surgeons.

APPENDIX: JOINT ANGLE MEASUREMENT

We placed magnetic pose trackers as close as possible to the centers of the joints (x_i and R_i, $i = t; w; e; s$ in Fig. 12A). Because the elbow sensor readouts were distorted due to magnetic interference from the da Vinci armrest, we estimated the position of the elbow joint, $\hat{x}_e[t]$, as the spatial average of two estimations:

$$\hat{x}^s_e[t] = x_s[t] + \hat{L}_{se} r_{xs}[t]; \quad (15)$$

$$\hat{x}^w_e[t] = x_w[t] + \hat{L}_{ew} r_{xw}[t]; \quad (16)$$

where $x_{(s=w)}$ and $r_{x(s=w)}$ are the position and the direction of the longitudinal axes of the shoulder/wrist sensors that were aligned with upper arm and forearm, respectively, and $\hat{L}_{se}$, and $\hat{L}_{ew}$ are the measured lengths of the upper arm, forearm, and hand, respectively (Fig. 12).

To assess the accuracy of our estimation algorithm, we recorded one experimental session in a metal-free environment, and calculated the average error between $\hat{x}_e[t]$ and the reading of the sensor located as close as anatomical constraints allowed to the center of the elbow joint, $x_e[t]$, which was (mean _ std) 20 _ 5 mm. The bias is likely related to inaccuracy of sensor placement, and the variance to their movement due to movement of the skin, which affects the orientation of the wrist and shoulder sensors as well as the position of the elbow sensor.

Estimation of the orientation of a pose tracker is more sensitive to accurate marker placement and skin movement than estimation of its position. Therefore, we estimated the orientations of the hand, forearm, and upper from the estimated positions of adjacent joint centers in 3D. We also estimated the limb segment lengths (L_{wt}, L_{ew}, and L_{se}, respectively) by calculating the median value of the distances between the appropriate joint centers across all the trials of each participant, rather than using the measured values.

To assess the effects of the different sources of estimation errors on our analysis, we calculated the mean distance between the measured master tool-tip path and its reconstruction based on the forward kinematics from the extracted joint angles.

The gripper-tip path is estimated more accurately than the rest of the magnetic pose trackers, because its pose tracker was rigidly attached to the grasp fixture, and because it was very close to the magnetic transmitter leading to an improved signal quality compared to the other sensors. The forward kinematics reconstruction error was 8:5 _ 0:13 mm (mean _ std). This error was statistically significantly smaller in the freehand condition compared to teleoperated (16%; $F_{1;1788}$ = 18; p < 0:001), and in the expert group compared to novice group (9%; $F_{1;1788}$ = 8; p = 0:005).

In addition, we used a Jacobian-based linearization of the forward kinematics. The mean reconstruction error of the linearized approximation was 11:5 _ 0:16 mm. It was also statistically significantly smaller in the freehand condition compared to teleoperated (24%; $F_{1;1788}$ = 49; p < 0:001), and in the expert group compared to novice group (23%; $F_{1;1788}$ =

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