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DOI
10.1115/1.4046797

Publication date
2020

Document Version
Final published version

Published in
Journal of Medical Devices, Transactions of the ASME

Evaluation of an Improved Suspension System Concept for Surgical Luminaires

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Surgeons have indicated ergonomic problems with the surgical luminaire, which have been observed to occur during repositioning. The possibility of singularity, within the movement space of the translational subsystem of the current double-arm suspension systems, is confirmed to be the cause of these problems. In this study, a redesign of the translational subsystem is compared to the conventional translational subsystem. A user experiment with 14 participants is setup to compare the redesigned and alternative system. The experiment is performed outside the operating room (OR), with one setup that can be altered between two designs; an uncoupled state with the kinematics of the conventional subsystem, and a coupled state with the redesigned kinematics. Work cost, duration, and jerk cost are compared, as well as NASA TLX score. The work cost of a movement in the conventional uncoupled state is confirmed to depend on the spatial orientation of the mechanism, which is not the case in the new coupled state. Due to these different kinetics, the movement patterns with the coupled mechanism are more consistent between participants, the duration of movements is shorter, less problems occur, and participants are able to better control the movements as demonstrated by lower jerk costs. This result validates the redesign and confirms the hypothesis that a translational subsystem without the possibility of singularity within its movement space will improve luminaire repositioning. The conceptual design can now be used as base for a clinically usable design. [DOI: 10.1115/1.4046797]

Introduction

Complaints of surgeons regarding the usability of surgical lighting [1,2] have been supported with more recent observations of difficulties in luminaire repositioning during surgical procedures in the operating room (OR) [3]. Repositioning duration was used here as an indicator for the occurrence of repositioning problems. These difficulties have been confirmed to be related to the kinematics of the translational subsystem of the current default double-arm suspension system. Due to the possibility of singularity, the force required to reposition the luminaire is dependent on the spatial arrangement of the mechanism [4]. As a result, the surgeon needs more time, more force, and more control effort to position the surgical lights, drawing his attention longer away from the clinical task [3,5]. This was observed to happen during surgery in standing and sitting postures [3].

The surgical light suspension system consists of a fixed ceiling mount and a two-link pendant system that rotates the links around the ceiling mount. The area close to the ceiling mount is prone to high forces and singularity [4]. This design is referred to as “the uncoupled state.” Based on these findings, the goal has been set to design a surgical luminaire suspension system that improves luminaire repositioning. It was hypothesized that a suspension mechanism without the possibility of singularity will improve luminaire repositioning. The resulting design is an adaptation of the conventional suspension mechanism, which is optimized for the required movement space [6].

The adaptations consist of a rail system from which the mechanism is suspended and a wrapping pair that couples the two vertical rotations of the pendant-type mechanism. This basically results in two independent orthogonal translational motions of the surgical light, instead of rotations around a fixed ceiling mount [6]. As a result, the mechanism does not contain singularity within its movement space. The rail mechanism can be integrated between the air inlets of current state-of-the-art two (or three) temperature plenums and the pendant-type mechanism currently present in the OR. Therefore, the design is considered most feasible. This design is referred to as “the coupled state.”

The goal of this experiment is to validate the design of the new mechanism and the hypothesis, by answering the following two research questions;

- Are the forces required to reposition the luminaire in the new mechanism consistent with movement velocity and independent of the spatial configuration?
- What is the reduction in repositioning duration if repositioning forces are consistent with movement velocity and independent of the spatial configuration?
- What is the reduction in control effort for the human operator if repositioning forces are consistent with movement velocity and independent of the spatial configuration?

Methods

Data on repositioning duration and problems with the current suspension were derived from observations of luminaire usage during surgical procedures [3]. Due to regulations and restrictions, it was not possible to test a conceptual system during a surgical procedure or in the OR. Thus, improvements in usage were validated outside the OR-environment and measured relative to the current standard.

Setup. The prototype was built using the Acrobat 2000 suspension mechanism supplied by the German manufacturer Ondal. This mechanism consists of a ceiling flange with a down-tube of approximately 350 mm in length (10.6 kg), an extension arm of 600 mm in length (2.6 kg), and a spring-arm with a length of 910 mm (6.2 kg).

A wrapping pair was added to the suspension mechanism, and the assembly was suspended from an existing linear joint test rig. These adaptations were designed in such a way that the prototype

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Manuscript received December 23, 2019; final manuscript received March 13, 2020; published online April 10, 2020. Assoc. Editor: Kunal Mitra.

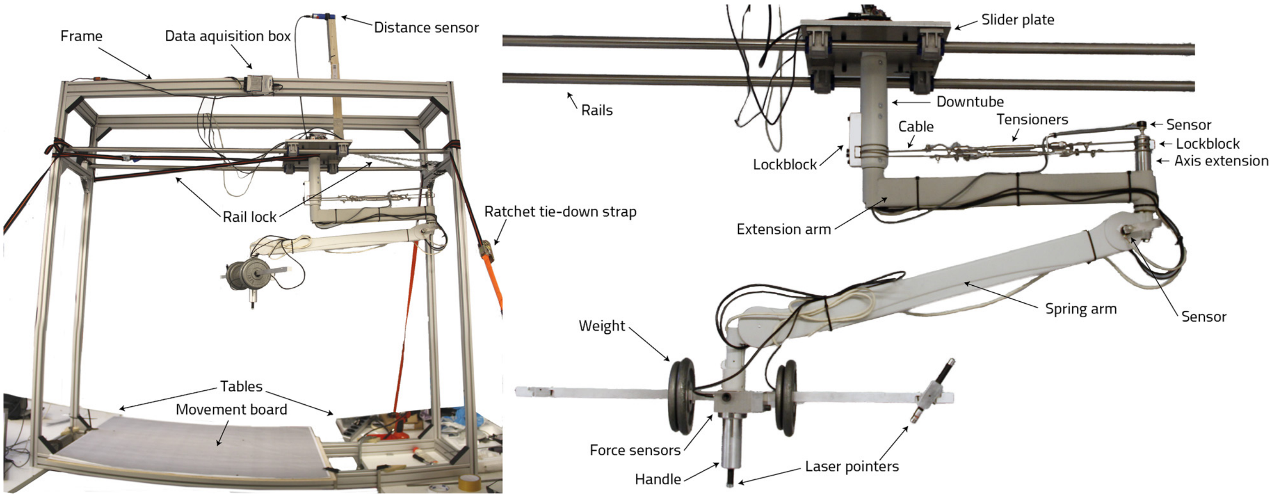

Fig. 1 The experimental setup on the left and a close-up of the prototype on the right. The experimental setup is photographed in the conventional uncoupled state. The close-up is of the coupled state.

can be easily switched between two states: the conventional uncoupled state and the conceptual coupled state (Fig. 1) [6].

Frame and Linear Joint. The ceiling flange of the Acrobat mechanism was fixed to an aluminum slider plate that moves with four linear rolling bearings (SKF) on two steel bars. The steel bars had a diameter of 25 mm, were 1900 mm in length, and were spaced at 400 mm. The bars were suspended at a height of approximately 1600 mm in an aluminum frame of Minitec profiles, that measures $2000 \times 2000 \times 460\,\mathrm{mm}^3$. The frame was set on top of two tables at a height of 850 mm, to elevate the center of the vertical movement area to approximately 1700 mm from the floor. The frame was fixed to the tables at both ends by clamps and ratchet tie down straps, for lateral stability.

In the uncoupled state, the rail is locked by fixing the slider to the frame, this is done by a chain on one side and a ratchet tie down strap at the other side. This ensures that the slider is always locked at exactly the same position.

Joint Coupling. In the coupled state, the two vertical rotations in the Acrobat suspension system were coupled with a steel cable wrapping pair, consisting of a 3 mm diameter cable (7×19 AISI 316) and two rigging screws for tensioning and easy disconnection. The cable was wrapped around the suspensions down-tube and secured with a custom lock block. At the other end of the extension arm, the axis of the spring-arm was extended with a custom made axis extension to which the cable was locked in a similar fashion. The diameter of the down-tube was 60 mm and the diameter of the axis extension was 32 mm, which was the optimal ratio for the chosen suspension dimensions. Before usage, the cable was prestressed, so that the system response was sufficiently stiff and added joint friction remained within limits.

End-Effector. In the OR, the suspension translations are operated through a large luminaire with a sterile handle that can be rotated around two or three axis. To imitate such an input device, the designed end-effector could rotate around the vertical axis and was equipped with a handle and a crossbar. The end-effector featured only one rotation as the improvement—and thus the experiment—was limited to the translation subsystem. The handle featured a blue laser pointer and was dimensioned with a diameter of 41 mm and a grip length of 100 mm. The crossbar was 900 mm in length, to imitate the diameter of a surgical luminaire. At one end of the crossbeam, a red laser pointer was connected that could be rotated between two preset angles. Weight was added to the crossbar to stabilize the gravity compensating mechanism in the spring-arm and to imitate the inertia of a luminaire. The total weight of the end-effector was approximately 9 kg.

Movement-Board. Four black dots with a diameter of 10 mm were printed on the gray movement-board in rectangular pattern of $500\,\mathrm{mm} \times 800\,\mathrm{mm}$ (Fig. 2). The two laser pointers in the end-effector were directed at this surface placed on top of the frame profiles below the end-effector. The crossing point of the red and blue laser beams imitated the focal point of a surgical luminaire. The distance between this focal point and the center of the handle was determined by the two preset angles of the red laser pointer. The first at which the spring-arm is slightly below horizontal, and the second at which the spring-arm slightly above the lowest setting. In both settings, up or down movement of the end-effector causes the laser dots to move apart on the movement-board.

Data Acquisition. All degrees-of-freedom in the prototype were outfitted with a sensor, to measure positions of the end-effector.

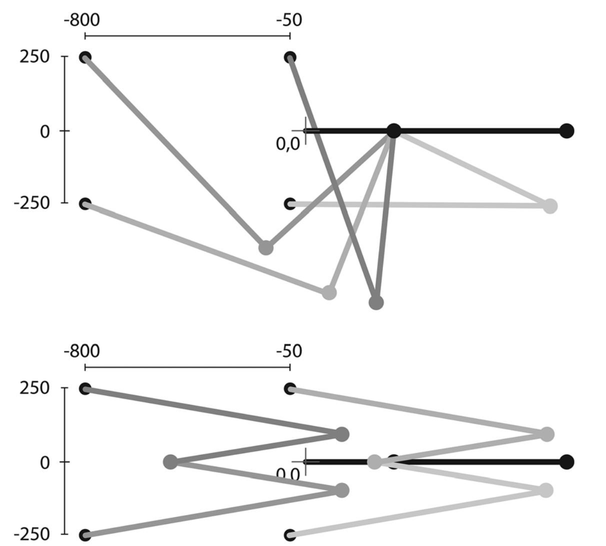

Fig. 2 The movement-board measures $500 \times 800\,\mathrm{mm}^2$. The board is positioned 50 mm left of the calibration point (0,0), and underneath the rail that moves along the horizontal axis. Five spatial configurations of mechanism are depicted for the conventional uncoupled state (above) and the conceptual coupled state (below). Four configurations for each of the markers and the calibration configuration. The latter is a singular position for the uncoupled system state. In this report, the markers are referred to as top-left, top-right, bottom-left, and bottom-right.

Also the handle was outfitted with two force sensors, to measure all control forces in the horizontal plane.

- The four rotations of the mechanism were measured by four potentiometers (Altheris fcp22e 5 kΩ ∼3%), which were connected to a nine volt battery and map the angle within the nine volt range at a linearity of ∼0.5%. The potentiometers were connected to the setup with sticky tape and glue.
- The translation of the rail system was measured with an ultrasonic distance sensor (PIL P43-T4V-2D-1C0-130E), which was aimed at the wall next to the setup. The ultrasonic sensor was powered by a standard 24 volt DC adapter.
- The forces at the end-effector were measured by two force sensors (Scaime ZFA 25 kg and ZFA 100 kg) that were mounted perpendicular between the handle and the end-effector, in such a way that the sensors did not interfere and measure all forces in the horizontal plane.

The potentiometers and the distance sensor were connected to a National Instruments USB-6008 data acquisition device and the force sensors were connected to a National Instruments USB-9162 data acquisition device running at high-speed timing mode. Both devices were connected to a Dell Latitude E6510 laptop which was running the National Instruments DAQmx drivers and the LabView data acquisition software. The LabView program sampled all sensor output at a rate 100 Hz and generated a tab separated file format. Furthermore, all the user experiments were captured on 1080 p video, using a Canon EOS 650D DSLR camera. This camera was setup to capture the movement-board and suspension system in one shot, for later reviewing of the participant's performance.

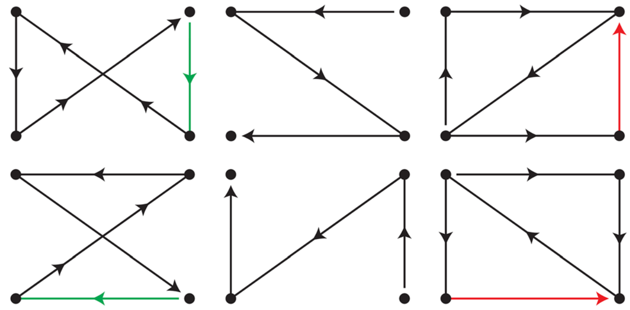

Fig. 3 From left to right, the sequence of the 12 movements that are performed twice by all subjects, once with the suspension system in uncoupled state and once with the suspension system in coupled state. The upper sequence is performed in a standing posture, the lower sequence is performed in a sitting posture. The green arrow is the first movement, and the red arrow is the last movement. Both sequences contain the same movements that can be divided in three types of movement; diagonal, *x* and *y*.

Experiment. The experiment was designed to capture human interaction with all three degrees-of-freedom of the suspension's translational subsystem.

Task. The participant was asked to position both laser dots in one of the black markers on the movement-board and to confirm when that position could be maintained without releasing the handle. Hereafter, the next marker was specified, and the subject was signaled to start the movement to the next position. A complete sequence existed 12 movements, containing every movement between all four points (three categories); four movements along the *x*-axis (from left to right and vice versa), four movements along the *y*-axis (from top to bottom and vice versa), and four diagonal movements. The movement-board was located 50 mm left of the calibration point (0,0 in Fig. 2) and was orientated with the *x*-axis parallel to the rail. Therefore, only diagonal movements required simultaneous control of both degrees-of-freedom in the coupled mechanism, and the uncoupled mechanism was only operated close to singularity at the right side of the movement-board (Fig. 2).

There were two movement sequences, one for a standing posture and one for a sitting posture (Fig. 3). In the complete task both sequences were performed twice, once with the suspension system in the coupled state and once with the suspension in the uncoupled state. For the sitting posture, a laboratory chair with caster wheels was used at a height setting that was preferred by the subject, and the spring-arm was lowered by approximately 400 mm. This shortened the length of the spring-arm in the horizontal plain and thus changed the system's kinetics.

Before the start of each sequence, the subject was asked to practice until he or she perceived to have reached the optimum in the speed of movement within their control. The assignment was not further specified to prevent the subject from optimizing their performance on a certain goal, so that the intuitiveness of the system is captured in the experiment. During the task, the subject was not allowed to touch the table or any part of the setup other than the handle and the movements were performed single handed.

Participants. The group of participants consisted of ten male students, two female students, a male surgeon specialized in the field of gynecology and a male surgeon specialized in the field of neurology. All participants enrolled in the experiments voluntarily. The participants were subdivided in two groups of five male students, one female student, and a surgeon. The first group used the system in the uncoupled state first and the second group used the system in the coupled state first. As such, the learning effects are equal in both mechanisms.

Questionnaire. After completion of the task with the system in one of both states, the participants were asked to complete a short questionnaire detailing the usage experience. The questionnaire was based on the NASA Task Load Index and assessed the workload on six different subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration [7]. After the experiment, all participants were asked to complete a second questionnaire that asked the overall experience and relevant demographics.

Data Analysis. The obtained data-files were analyzed using MATLAB. The position data were calibrated with values obtained in the calibration configuration (Fig. 2) at the start of every sequence and filtered with a third-order Butterworth low-pass filter with a cut-off frequency of 5 Hz. These data were used to calculate the positions and rotations of the end-effector relative to the movement-board with forward kinematic equations of the setup. To check the results, the setup movements were plotted in a top-view and compared with the captured video of the experiments. The data of the force sensors were also filtered with a third-order Butterworth low-pass filter with a cut-off frequency of 5 Hz and corrected for the rotations of the end-effector. Every movement in the sequence was isolated based on a marker value in the dataset, which indicates the signal given to start a movement and the confirmation of arrival signal given by the participant. This value was manually updated during the measurements relative to the movement-board.

Indicators. To answer the first research question, force (f) and movement velocity (change in position ds during change of time dt: ds/dt) are used as indicators. These indicators are combined in the work (W) measure (Eq. (1)), which calculates the energy cost of a movement in Joule. A paired measure (W_p) of one movement in opposite directions by one participant (W_1 and W_2) for both mechanism states and both postures is compared (Eq. (2)). If the required forces for repositioning are consistent with movement speed and independent of the suspension's spatial configuration, it is expected that equal movements in opposite directions cost similar amounts of energy for one participant. Thus, that the paired measure is zero or close to zero

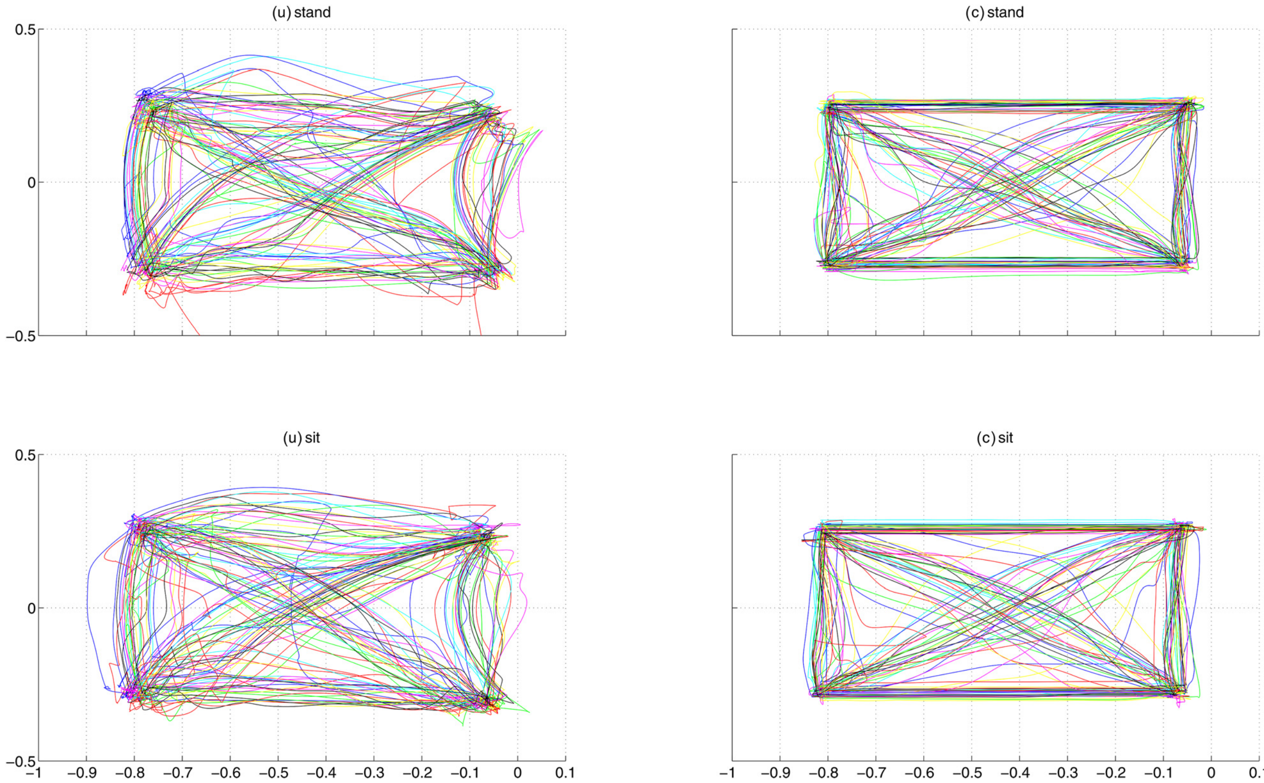

Fig. 4 The movement paths of the end-effector of all participants, plotted on the movement-board. The movements with the conventional uncoupled mechanism are plotted at the left and with the conceptual coupled mechanism at the right. The upper figures are of the movements performed in a standing posture and the lower figures of the performance in a sitting posture. It can be observed that the perpendicular translations in the coupled mechanism create straight movement paths, whereas the uncoupled mechanism is moved along curved paths.

$$W = \int (f \cdot (ds/dt)) \cdot dt \tag{1}$$

$$W_p = W_1 - W_2 \tag{2}$$

The second research question refers to previous research, in which outliers in movement duration are an indicator of problems that occur during positioning. The duration of a movement (t_m) is defined as the end-time (t_{end}) minus the start-time (t_{start}) of that movement. Outliers are registered and inspected in the video capture of the experiments, and the observed problems and relevant measurements are discussed.

The third research question relates to repositioning control effort. Several theoretical models exist that describe human hand movement for the assessment of motion disorders and movement quality [8]. Although no publications have been found that connect usability to a movement quality indicator, the indicators are aimed to reveal information about healthy unconstraint point to point motion, and it can be theorized that this is the preferred motion for humans.

An early and influential descriptive model is the minimum-jerk model, which is based on the observation that—in unconstraint point to point movements in the horizontal plane—humans strive to "generate the smoothest motion to bring the hand from the initial position to the final position in a given time" [9]. Such motion is characterized by a bell-shaped velocity profile, which is acquired by the minimization of the jerk cost function. The cost function (CF) is the integral of the squared jerk (change in acceleration over time) in all directions (x, y, and z) over the interval of the movement

$$\text{CF} = \int \left((d^3x/dt^3)^2 + (d^3y/dt^3)^2 + (d^3z/dt^3)^2 \right) * dt \tag{3}$$

Statistics. The analysis was performed using the statistics toolbox of MATLAB 7.14. The data were paired on participant and movement, grouped by the three movement types (diagonal, x and y), and compared on two factors (state and posture), by means of a two-way repeated measures analysis of variance. The same paired data, grouped by movement type and state (or posture), were also compared on posture (or state), by means of a repeated measures ANOVA and a Wilcoxon signed rank test. Furthermore, three comparisons were done within each posture–state combination, between the movement types, by means of a t-test and a Wilcoxon signed rank test. The result of the Wilcoxon is used in cases of insufficient normality, which is tested by means of a Lilliefors test. $p < 0.05$ is considered significant.

Results

A plot of the movements of all participants gives an overview of the difference in movement paths between participants, postures, and mechanism states (Fig. 4). It can be observed that the movements with the uncoupled mechanism are less consistent and contain several radical outliers. The parts in which most participants seem to perform equal are mostly circular shaped segments with the uncoupled mechanism, and straight segments with the coupled mechanism. No specific differentiations can be seen between the postures.

A visualization of the input forces along an exemplary movement path shows the difference in force magnitude and direction between the two system states (Fig. 5). It can be observed that the forces in the uncoupled system are much larger and seem arbitrary in direction, whereas the forces in the coupled mechanism show an acceleration in one direction and deceleration in the opposite direction. No outstanding differences can be distinguished between the performance of an expert (surgeon) and that of a novice (student).

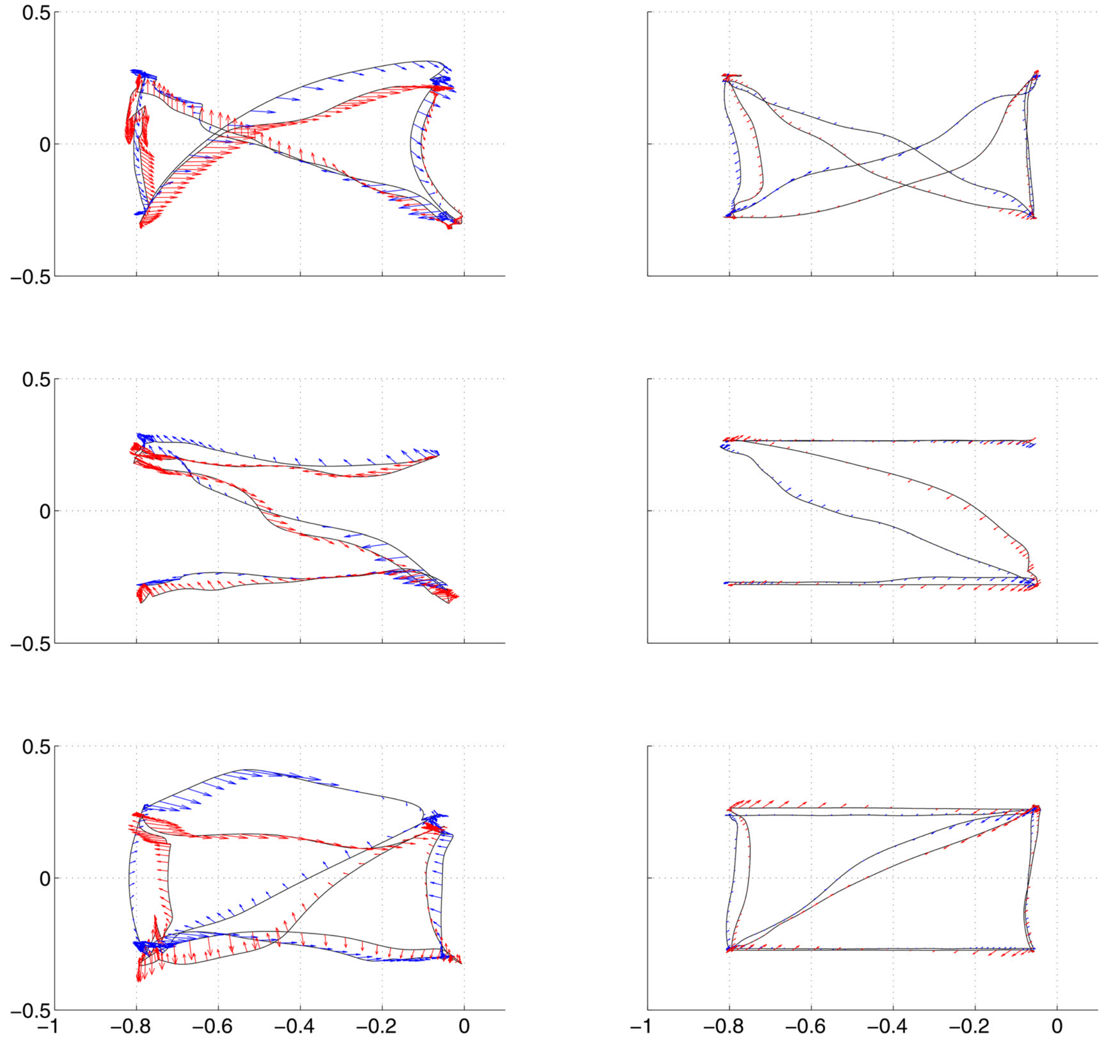

Fig. 5 Force magnitude (arrow lengths) and direction (arrow directions) along a couple of traveled paths (black lines). Uncoupled (left panels) and coupled (right panels).

Work. The average work is calculated for every participant per movement type (diagonal, x and y) with both mechanism states and in both postures, thus 12 sets of 14 values (Fig. 6). In a comparison of the movements in equal mechanism states (between postures), no difference occurs in the uncoupled state ($p > 0.05$).

In the coupled state, the X movements have a lower work cost in standing posture ($f(1,13) = 4.92$, $p < 0.05$) and the Y-movements have a lower work cost in a sitting posture ($f(1,13) = 5.12$, $p < 0.05$). When movements in the different mechanism states are compared (within postures), the work cost of the diagonal and X movements is less in the coupled state ($f(1,55) = 117$ and $f(1,55) = 338$, $p < 0.01$) and the work cost is of the y-movements is equal ($f(1,55) = 0.29$, $p > 0.05$).

Within each posture-state combination, the work cost between movement types is different, except for the diagonal and horizontal movement in the uncoupled state ($f(1,55) = 1.79$, $p > 0.05$). The paired difference is calculated for all six trajectories in the movement sequence, between the movements in opposite direction, for all four posture-state combinations and for all participants. Thus, resulting in 24 sets of 14 value. Also for this indicator, the mechanism states shows great similarities between postures and a clear difference within postures. For the uncoupled state, in all movement directions, the work cost of opposite movements is different ($p < 0.05$) except for the Y-movement at the right side of the movement-board ($t = 1.29(13)$ and $t = 0.22(13)$, $p > 0.05$). For the coupled, the results are contrary; for all movement directions, the work cost of opposite movements is equal ($p > 0.05$), except for the Y-movement at the right side in standing posture ($t = 4.54(13)$, $p < 0.01$) and the Y-movement at the left side in sitting posture ($t = 5.11(13)$, $p < 0.01$).

Movement Duration and Problems. The movement duration is calculated for every participant per movement type (diagonal, X and Y) with both mechanism states and in both postures, thus 12 sets of 14 values (Fig. 7). Also, for this indicator, the mechanism states are equal between postures ($p > 0.05$), and show a clear difference within postures. The coupled mechanism is positioned within less time than the uncoupled mechanism ($p < 0.01$). Furthermore, it can be observed that the variance in duration and the amount of duration outliers is less for the coupled mechanism (Fig. 7). This implies that less problems are encountered and that the performance of participants is more consistent. This is supported by the selection of movements with a duration longer than 9 s, in which the uncoupled system state is predominant and both postures are approximately equally represented. In this group, it can be observed that two female participants and one male participant are responsible for 67% of the outliers above 9 s and that both surgeons are present in the other 33% with five movements that were executed with the uncoupled mechanism. Through a review of the captured video for the movements with the longest movement durations of several participants, a variety of problems

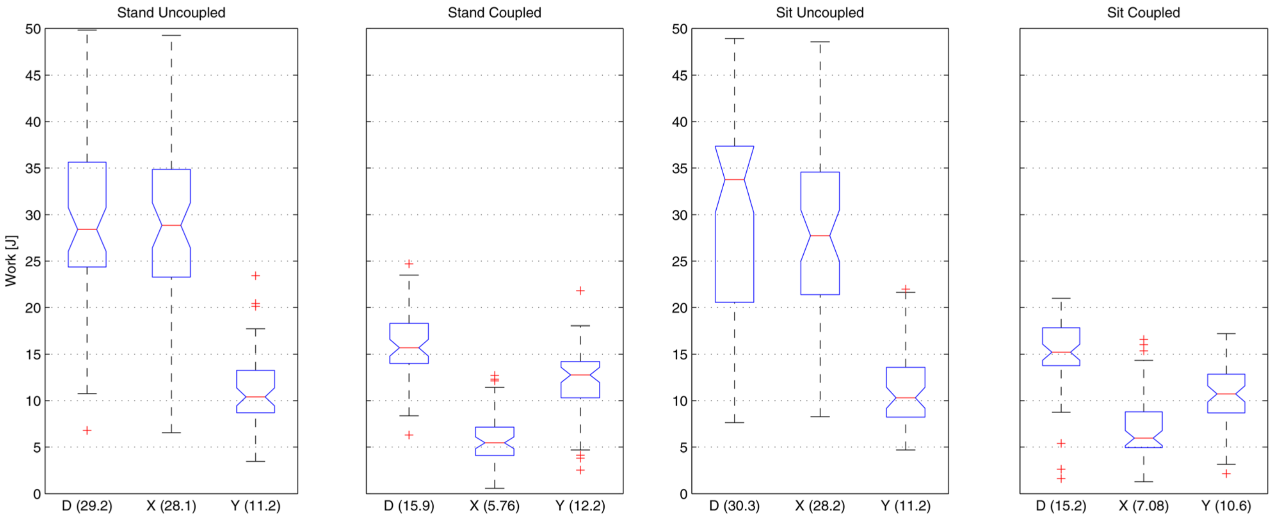

Fig. 6 The average work values in Joule for all participants, grouped by posture, state, and movement type; diagonal (*D*), *X* and *Y*. Nonoverlapping notches show that medians differ at a 5% significance level. Thus, it can be observed that there is no difference between postures and that there is difference between system states except for the *y*-movements. As a reference, the work value of 25 J is approximately equivalent to lifting 2.5 kg to a height of 1 m.

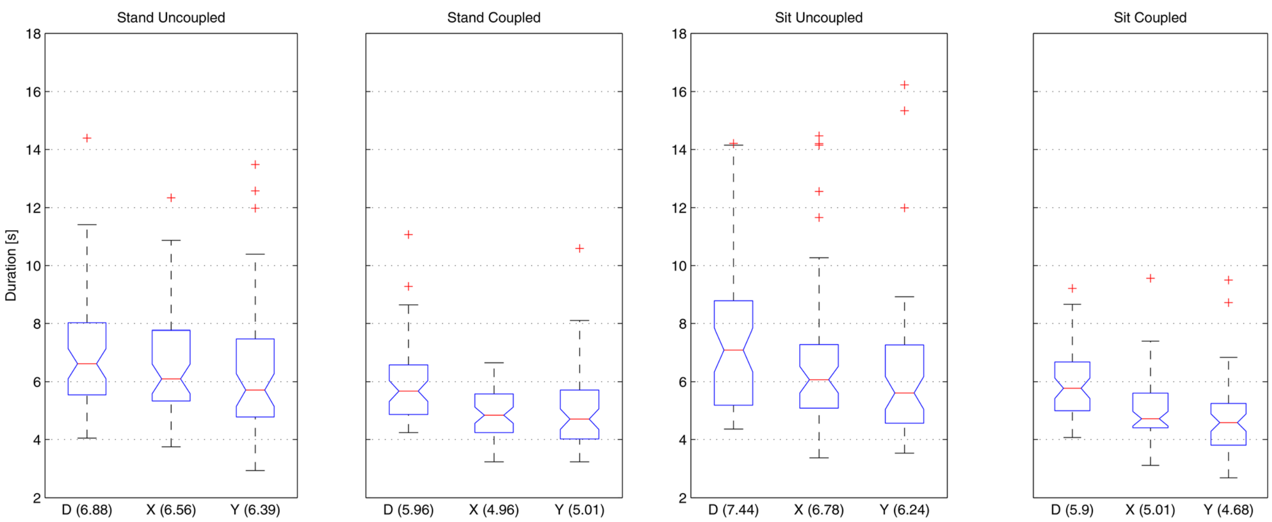

Fig. 7 The duration of each movement for all participants, grouped by posture, system state, and movement type; diagonal (*D*), X, and Y. It can be observed that the duration of movements made with the coupled mechanism is shorter on average. However, the notches denote the 5% significance, which shows that the duration difference is insignificant for *y*-movements.

are observed. These problems often cause the participant's attention to shift to the suspension, away from the task at the movement-board. Three common causes can be distinguished.

Friction and Precision. The friction in the plain bearing of the rotational joint between the down-tube and the extension arm increases when the end-effector is further from the down-tube. As a result, the movements with the uncoupled mechanism at the left side of the movement-board (Fig. 8, left) and toward the right side have an increased difficulty. This specifically causes difficulties during more precise positioning near the end part of the movement, which is a problem that exists in every movement in the uncoupled mechanism.

Collisions. The hand that is holding the end-effector rotates along with trunk of the participant during *X* movements. This rotation can cause the cross beam to hit the two vertical beams at the left side of the setup. In the worst case, the cross beam is pushed between the two vertical beams in the movement from bottom-left to top-left (Fig. 8, right). The mean durations of all *y*-movements at the left side with the uncoupled mechanism is 6.71 (s) and 5.25 (s) with the uncoupled mechanism ($f(1,11) = 14.9$ $p < 0.01$).

Singularity. At the right side of the movement-board several participants reach a singular spatial configuration with the uncoupled mechanism, in the movement from bottom-right to top-right. Although this movement does not contain any singular points, the human controller is apparently "tempted" to follow the rotations of the spring-arm. The resulting (close to) singular configuration is resolved by reversing the movement or by the exertion of an increased amount of force (Fig. 9). The mean duration of the upward *y*-movements at the right side with the uncoupled mechanism is 6.35 (s) and 4.57 (s) with the coupled mechanism ($f(1,55) = 17.2$ $p < 0.01$).

Because collisions and singularity occur in the *y*-movements at both sides of the movement-board, *y*-movements that take longer than 7.8 s (>75th percentile) are analyzed; 84% ($n = 27$) of these movements are performed with the uncoupled mechanism and 58% occurred at the left side of the movement-board. The three previously mentioned participants are also predominant in this

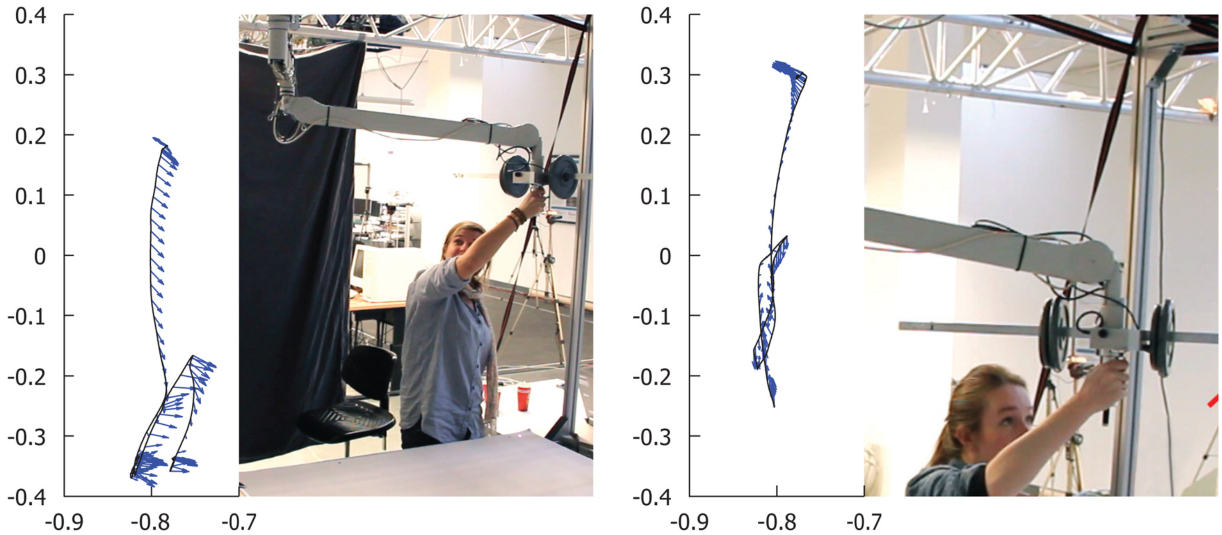

Fig. 8 The traveled path is depicted to the left of a video still of two occurring problems; (left) relative high friction in the suspension causes the participant to repeatedly overshoot the target caused by the build-up of force to overcome friction in precise movements. (Right) Rotations of the end-effector causes collisions or entanglement of the cross beam with the setup frame. The depicted case is the most severe, in which the suspension is completely retracted before the movement can be completed.

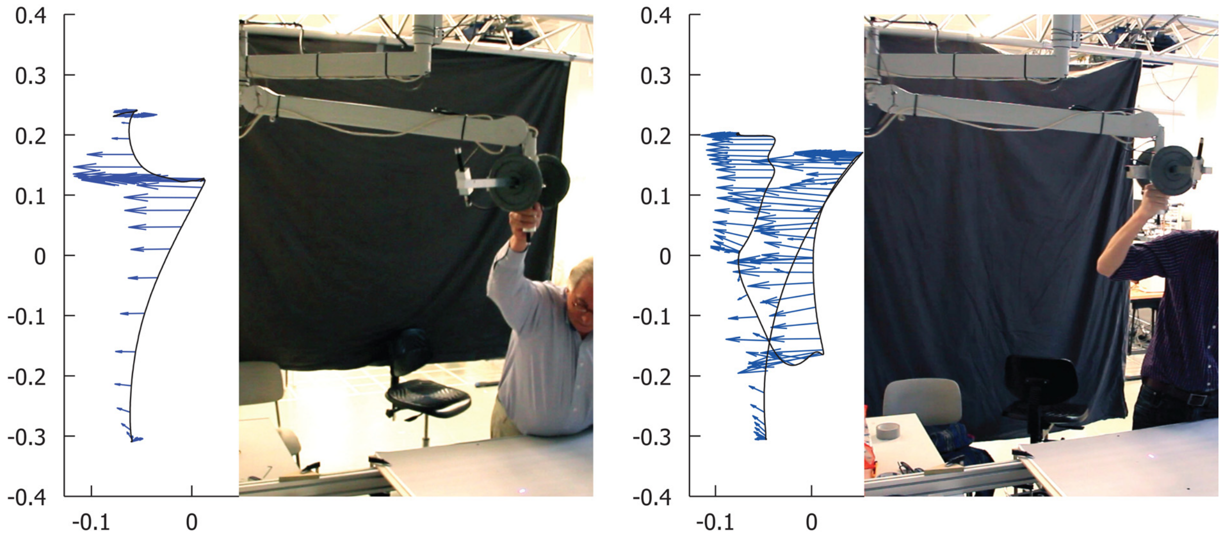

Fig. 9 Two cases of a longer movement duration caused by singularity; the traveled path is depicted to the left of a video still of the occurrence of the problem. This problem only occurs in the movement from bottom-right to top-right. The situation is often resolved by an increased input of force without looking away from the task (as the neurosurgeon on the left demonstrates). Or the situation is resolved by inspection of the mechanism followed by retraction and a retry on a different path (as the student on the right demonstrates).

selection with 65% of the movements and again both surgeons are among the other 35% with four movements executed with the uncoupled mechanism.

Jerk Cost. The jerk cost is calculated for every participant per movement type (diagonal, *X* and *Y*) with both mechanism states and in both postures, thus 12 sets of 14 values (Fig. 10). Again it was observed that performances in the mechanism states are very similar between postures. There are no differences in the coupled state ($p > 0.05$). In the uncoupled state, the jerk cost in diagonal and *X* movement is larger in sitting position ($z = 2.10$ and $z = 2.19$, $p < 0.05$).

Within postures, the difference between the conventional uncoupled mechanism and the conceptual coupled mechanism is very distinct ($p < 0.01$). For diagonal and Y-movements, the jerk cost in the coupled state is approximately half the cost in the uncoupled state. For *X* movements this is approximately a fifth. Within each posture-state combination, the jerk cost differs significantly for the coupled state in both postures ($p < 0.01$). For the uncoupled state no difference exists between the jerk in *X*- and *Y*-movements in both postures ($f(1,55) = 0.65$, $p > 0.05$).

Furthermore, the variance of the distributions is much smaller for the coupled mechanism and its incidence among the highest scoring movements is very low. Based on the analysis of the captured video for the highest scoring results, it appears that high friction and singularity are a main cause for a high jerk cost.

Questionnaire Results. The results of the questionnaire that was completed after the experiment are very unambiguous and in favor of the coupled system, approximately 93% of the participants answered that the uncoupled system required most force to

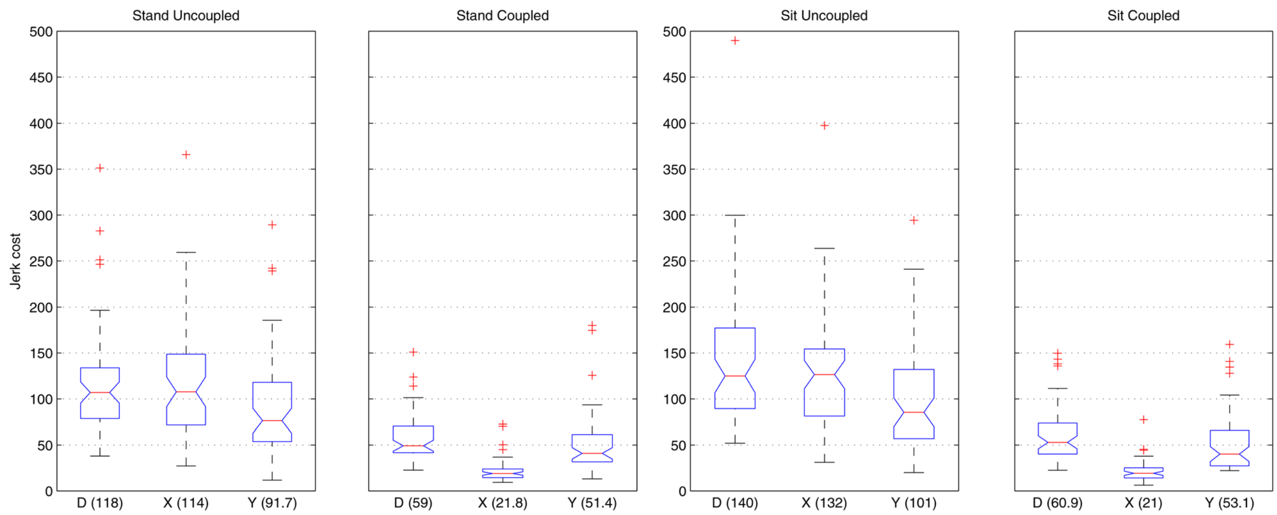

Fig. 10 Jerk cost of for various scenarios depicted as boxplots

move and 91% answered to have more control over the movements of the coupled system. The results of the TLX questionnaire are verified using a paired one-sided *t*-test. According to this test, there is no difference in mental demand between the mechanism states ($t = 2.07(13)$, $p > 0.05$), all other questions are answered in favor of the conceptual coupled mechanism ($p < 0.05$).

Also, from the answers to a number of other relevant questions, the effect of the coupled mechanism appeared to be positive. However, the *y*-movements are mainly regarded to be annoying in both mechanisms stated, and with both mechanism, the participants felt that they could improve their performance by practicing for a long period. Furthermore, most participants indicated that movements to the right of the movement-board were strenuous in the uncoupled mechanism, due to a large difference between the friction in the rail and the suspension. Also, the low friction in the rail was repeatedly indicated to cause overshoot of the target.

Discussion

This study shows an explicit difference in manual repositioning performance between the new coupled translational subsystem and the conventional uncoupled subsystem. The movement patterns described with the new mechanism show more efficiency and consistency. Which is quantified by the indicator outcome and favored by the participants.

The aim of this study was to validate the absence of singularity in the redesigned translational subsystem, and to subsequently test the hypothesis that the kinematic change improves repositioning. This was researched via a user experiment with 14 participants, who executed a sequence of repositioning movements with one test setup, in both the conventional uncoupled state, and the new coupled state.

The results show that the work required for two movements between equal points in opposite directions is inconsistent for the uncoupled mechanism. This is caused by inconsistency in the movement forces and velocity, which are apparently influenced by the differences in the mechanism's spatial configuration over the course of the opposite, but otherwise equal, movements. This effect was expected, because of the uncoupled mechanism's kinematics. The force input at the handle creates a certain torque at each joint, which depends on the spatial orientation of the mechanism, whereas the friction remains constant, and thus, the required movement force depends on the spatial orientation of the mechanism. For the coupled mechanism, the work required for the equal opposite movements is consistent, which demonstrates the absence of singularity within the movement space of the new mechanism design.

Furthermore, results show improvements in repositioning performance with the coupled mechanism, relative to repositioning with the conventional uncoupled mechanism. The movements are performed faster, and less problematic situations occur that cause outliers in the movement duration. Also, control effort is less, as the jerk cost of the movements is less, and the qualitative participant responses are in favor of the coupled system. However, there are two factors that have influenced the experiment and have to be taken into account for correct interpretation of these results; the movement pattern and friction differences.

Friction Differences. Movement of the rail mechanism was subject to little friction relative to the rotation of the suspension arms, which greatly reduced the work required for *X* movements in the coupled mechanism. Although this can be seen as an improvement of the kinetics, it is also of influence on indicators used to describe improvements of the kinematics. As a result, the only unbiased movement is the *Y*-movement. The equal work cost between states in both postures for this movement confirms equal friction characteristics.

The paired work indicator is a comparison within one system state and thus insensitive for interstate friction differences, because the same friction is present in the paired opposite movements. Therefore, the proof for absence of singularity in the new mechanism holds. Furthermore, the jerk cost measures the smoothness of the movement, which is sensitive for variations in the friction and not so much the magnitude (as long as it can be reasonably overcome by human power). Therefore, these indicators are considered to give insight into the effects of the different kinematics. However, the duration indicator is influenced by the difference in friction. Presumably, the duration of movements in the coupled mechanism would decrease when the friction in the revolute joints is lowered.

Movement Pattern. The second factor is the movement pattern, which was designed and positioned in such a manner that the degrees-of-freedom of the coupled system can be assessed separately (*Y* and *X* movements) and combined (diagonal movements). The effect manifests in the work cost of the movements with the coupled mechanism, in which the work that is required of diagonal movements approximates the sum of the work required for *X*- and *Y*-movements. The uncoupled mechanism can only complete the movements in the movement pattern with a combination of the two arm rotations, resulting in relatively arbitrary work. It can be expected that luminaire movements in the operating room will mostly require a combination of the degrees-of-freedom. Thus, a representative comparison of mechanism performance between states can only be performed between diagonal movements.

Improvement of Repositioning. With consideration of before mentioned factors, it can be concluded that the difference between the mechanism kinematics in the coupled mechanism improves the repositioning performance. The *Y*-movements with the coupled mechanism are executed 1.5 s faster (6.3–4.8), and there is a difference of approximately 20 J in opposite diagonal movements between the bottom–left and top–right markers, whereas the work cost for these movements is equal in the coupled mechanism. Furthermore, the significantly lowered squared jerk for the movements with the coupled mechanism shows that the kinematics of the coupled mechanism has resulted in improved usability. The factor two (or more) difference in jerk cost indicates that participants were able to better optimize the "smoothness" of the repositioning movements with the coupled mechanism. This directly translates to an improvement of usability. The improvement of usability is supported by the qualitative results. These show that participants significantly favor the coupled mechanism with regard to movement effort, movement control, movement force, and success of the movement. Also, participants felt their movements with the coupled mechanism were faster, easier, and less susceptible for collisions. However, it has to be taken into account that the lowered input forces that were required for horizontal and diagonal movement in the coupled mechanism can have contributed in a feeling of more control and a lower required control effort.

Recommendations. The results in this research are obtained outside the operating room, in a controlled environment, with a subsystem of the suspension system and through a task that was abstracted from the actual task of luminaire repositioning—in the operating room during an operation. Therefore, the design is only partially validated.

Also, many setups in the operating room consist of two luminaires. This would require two rails on each side of the operating table. To really improve the actual luminaire repositioning, the proposed mechanism has to be further validated in the operating room environment.

The design has to be further engineered to move from functional proof of concept to a clinical design that can be used in the operating room. This includes fitting the coupling design inside a covered embodiment and testing the influence of this new embodiment on disturbance of the laminar airflow, as well as detailing the rail system and testing the effect of rails on hygiene and falling dust. However, in some hybrid operating rooms rails are often used to move imaging equipment in and out the surgical area.

Conclusion

The significant difference in work cost that is required for a diagonal movement in opposite directions shows that the spatial arrangement influences the velocity and force required to perform a movement in the uncoupled system. In the coupled mechanism there is no significant difference between such movements, hence answering the first research question; the forces required to reposition the luminaire in the new mechanism are consistent with the movement velocity and independent of the spatial configuration.

A significant reduction in duration is observed for the coupled mechanism in movements with equal friction characteristics and the incidence of the coupled mechanism among movements with significantly high duration is low. Therefore, the second research question can be answered as follows; the repositioning duration and problems are significantly lower for a mechanism with movement forces that are consistent with movement velocity and independent of the spatial configuration.

The significant reduction in jerk costs for the coupled mechanism indicates that the control effort of the human operator is reduced when using the new mechanism. Therefore, the third research question can be answered as follows; the jerk costs are significantly lower for a mechanism with movement forces that are consistent with movement velocity and independent of the spatial configuration.

These answers together with the improvement in usability of the redesigned translational mechanism lead to the validation of the hypothesis; a suspension mechanism without singularity does improve luminaire repositioning. Hence, the research goal is accomplished, a suspension mechanism has been designed that improves luminaire repositioning.

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