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Ergonomics of Exoskeletons: Subjective Performance Metrics

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Abstract— **In this paper it is shown how variation of the kinematic structure of an arm exoskeleton and variation of its fixation pressure on the human limb influences subjectively perceived task performance, such as comfort and the individual indices of the NASA TLX rating scale.**

It is shown by experimental results that the attachment pressure has a dominant effect on perceived comfort, mental load, physical demand and effort experienced by subjects and is optimal within a range of 10 – 30 mmHg. Furthermore, it is shown that the inclusion of passive compensatory joints inside an exoskeleton's structure can reduce mental demand during a tracking task.

When the outcome of this paper is interpreted in combination with a set of objective performance results that were presented earlier [1], the subjective performance metrics underline the fact that passive compensatory joints paired with an attachment pressure of 20 mmHg increase ergonomics and provide optimal conditions for task performance and comfort.

I. Introduction

EXOSKELETONS are subject to intense interest and research at this point in time, for many applications spanning from haptics and fundamental haptic device research [2] over bilateral tele-robotics [3] and defense applications [4], up to the relatively new field of robotic physical therapy [5]. All types of wearable robots must be safe, comfortable and able to smoothly interact with the human user.

While issues of safety and physical human-robot interaction become increasingly popular as a scientific domain within the field of robotics research [6], exact investigations of influence on operator comfort and mental task performance with wearable robot systems has not been largely addressed in recent literature.

In our line of research [7], we aim to develop a mechanically transparent exoskeleton haptic device that is optimally ergonomic for its users. This requirement stems from the need for the exoskeleton to function as a haptic interface for Astronaut crew inside the International Space Station. Typically, operations in orbit can take very long, up to six or eight hours. This poses very high demands on compatibility of the device to its operators and to its comfort and ergonomics. Furthermore, an exoskeleton used by astronaut crew should allow for quick dress-on and dress-off and therefore not require mechanical adjustments of its limbs prior to changing operators.

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To achieve this goal, we particularly targeted the development towards building a device that can be robust to misalignments to the corresponding human joint centers of rotation. Such misalignments between an exoskeleton and a human joint is inevitable and can be the cause of significant disturbance forces that impact the human limb and lead to discomfort or even injury. The effect of misalignment in other known devices has caused discomfort to its users, which was reported in literature [8]. Within the field of rehabilitation robotics, for example, joint mismatches between wearable robots and their users have been proven responsible to lower effectiveness of treatment [9] [10]. Therefore, we have conceived a dedicated kinematic design that features passive compensation joints for such offset compensation [11]. We have shown earlier in [11] that the inclusion of passive compensatory joints in the exoskeleton increases the overall available workspace with the human arm, allows dress-on and dress-off within seconds for operator statues ranging from the 5^{th} – 95^{th} percentile of US male population and eliminates the need for mechanical adjustments on the exoskeleton between users.

This paper belongs to a new investigation that aimed at quantifying the detailed effects of human-to-robot joint misalignment and human-to-robot coupling strength variation, in particular their influence on objective and subjective performance metrics. This was tested in a signal tracking task with the wearable ESA EXARM exoskeleton [12]. The experimental results for objective criteria were already reported earlier in [1] but left some remaining questions open. Some key findings will be briefly summarized in Chapter III, to provide the reader with the necessary background to follow the latest results and discussion presented in this paper.

In [1] we showed that offsets between an exoskeleton joint and a human joint can always appear, even if the two systems were well aligned before the tracking task. We have also shown that the apparent offsets between the joints were responsible for the creation of large interface forces when no passive joints for offset compensation were set free to move in the exoskeleton. However, in [1] we did not report the effects on subjectively perceived comfort and mental load due to this variation.

It is the goal of this paper to quantify the influence of (1) attachment pressure of the exoskeleton fixation on the human limb and of (2) the presence/absence of passive compensation joints within the exoskeletons mechanical structure to subjective performance measures. The subjective performance measures applied in this paper are based on questionnaires for (1) comfort and (2) all six indices of the NASA TLX rating scale. The results shall determine the optimal attachment parameters and kinematic design choices for wearable exoskeletons, in order to increase comfort.

II. Method

A. Experimental Method

In order to quantify the effects of kinematic exoskeleton configuration and attachment pressure on subjective task performance, an experiment was conducted with 14 test subjects. All subjects were asked to track a target signal on a computer screen with the EXARM exoskeletons attached to their elbow. Fig. 1 depicts the elbow- and wrist-part of the exoskeleton as attached to an experiment subject. The EXARM's main elbow joint is denoted by Θ_7. Two passive compensation joints are included in the elbow-part. Both joints, the linear sliding-joint Δ_8 and the rotary compensation joint Θ_9 incorporate mechanical quick-locking pins that can block the motion of the joint if released. When the passive joints are both blocked, the linkage between the elbow joint Θ_7 and the forearm attachment-cuff becomes rigid and the entire articulation possesses only one primary joint, like most other known exoskeleton devices. This situation then corresponds to the illustration in Fig. 2 a. Forces F_d and Torques T_d can then be created when the joint center of rotation of human arm ICR_h and exoskeleton CR_e don't align. If both joints are free to move, the situation corresponds to the illustration in Fig. 2 b, where the passive joints reduce such interface forces. For all tracking trials, the control signal was commanded by the elbow joint potentiometer (inside Θ_7) of the exoskeleton interface. The air cushions used to apply the attachment pressure between the exoskeleton and the human arm are depicted in Fig. 1. The F/T Sensor was required for analyzing the objective results, in particular the interface loads reported in [1]. The kinematic and attachment settings of the exoskeleton were varied by an experimenter between runs, as will be explained below. After each trial, the subjects were asked to fill a subjective rating questionnaire.

B. Experimental Protocol

The 7 male and 7 female subjects (stature 1.75 m ± 0.09 m, mass: 68.7 kg ± 12.8 kg) were asked to track a random crested multisine signal v with their elbow. The frequency content of the target signal ranged from 0.05 – 0.35 Hz. The target signal was represented on a computer screen by a moving blue bar. The subjects were able to track the movement of the bar by moving their elbow inserted into the exoskeleton. All angles of the exoskeleton joints were measured and its principle elbow joint was used to control a second (green) bar that was displayed below the target signal on the computer screen. To provide visual feedback of the goodness of the tracking performance, a third red bar showed the instantaneous tracking error.

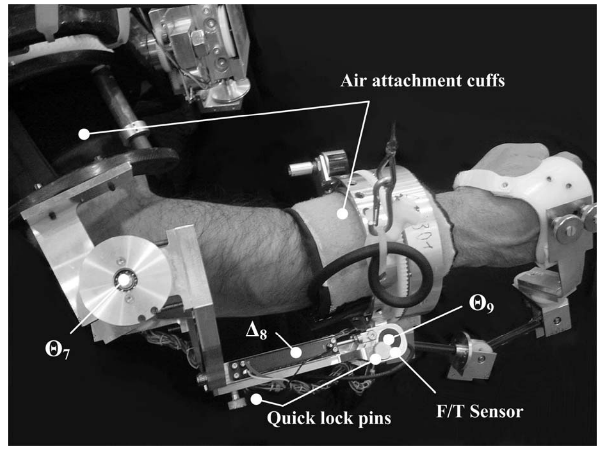

Fig. 1. Overview of the exoskeleton's elbow articulation that was used to control the tracking signals in the presented experimental study.

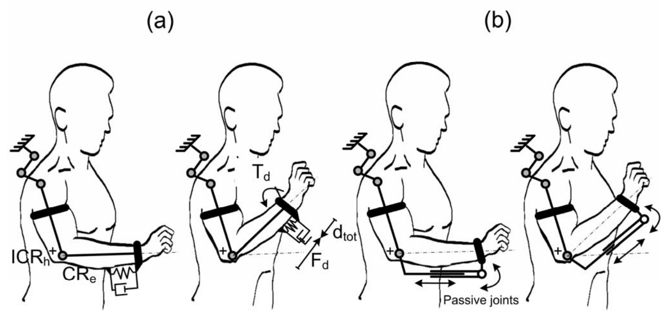

Fig. 2. Illustration of the two kinematic configurations in which the exoskeleton can be used. In (a), *'locked'* no passive joints are incorporated into the structure, leading to interface loading. In (b), *'unlocked'* passive joints act to reduce such interface loading between exoskeleton and human arm.

The target signal v demanded elbow flexion from 0 – 90 Deg.. Each experiment run took exactly 60 s.

Between runs, the attachment stiffness on the exoskeleton's upper and forearm air-cushions was randomly varied by the experimenter. By inflating/deflating the air-cushions, the experimenter was able to vary the air-cushion pressure from 10 – 60 mmHg, in steps of 10 mmHg. Both cusions were always set to the same pressure. Also, the kinematic setting of the exoskeleton was randomly changed between runs. The experimenter varied the kinematic exoskeleton structure between *locked* (*L*) and *free/unlocked* (*U*) settings. In the *U* setting, the passive joints were free to move – the setting in which, according to [1] least interface load is created, while in *L* setting all passive compensation joints of the exoskeleton were blocked – thus, creating significant interface loads. Each combination of factors, kinematic setting and attachment pressure was tested once per subject in random order, which resulted in 12 experiment trials to be carried out per subject. Before each trial, the EXARM was re-attached such, that the joint Θ_7 aligned as good as possible (by visual adjustment) to the human elbow joint. All subjects were blinded to the experiment conditions. The signal tracking motion was carried out with the arm elevated in a horizontal plane, to reduce effects of gravity on force measurements that were recorded for analyzing the results presented in [1].

After each trial, the subjects were asked to rate a subjective questionnaire on a visual rating scale with a pen. They marked their rating on 7 linear rating scales that ranged from 0 (low) to 100 (high) points. The rating scale was an extended NASA TLX questionnaire, as introduced in [13]. In detail, the questionnaire contained following fields:

- *(1) Comfort, – definition: How comfortable was this setting of the exoskeleton during movement?*
- *(2) Mental Demand (MD), – definition: How mentally demanding was the task?*
- *(3) Physical Demand (PD), – definition: How physically demanding was the task?*
- *(4) Temporal Demand (TD), – definition: How hurried or rushed was the pace of the task?*
- *(5) Performance (OP), – definition: How successful were you in accomplishing what you were asked to do?*
- *(6) Effort (EF), – definition: How hard did you have to work to accomplish your level of performance?*
- *(7) Frustration (FR), – definition: How insecure, discouraged, irritated, stressed, and annoyed were you?*

The task that was given verbally to the subjects was: *"Please track the target signal as good as you can."* After all 12 trials the weighting factors for the TLX rating scales were acquired for each subject by pair wise comparisons and computed into an overall set of group weights. Next, the experimenter asked the subjects which attachment pressures were the most comfortable ones. This was determined per subject by inflating the cuffs and asking the subjects to clearly indicate the most comfortable setting.

To get the subjects used to the set-up before the real experiment, a five-trial training session had been carried out. Pilot experiments had confirmed that this was sufficient to get the subjects used to the task. The test runs were conducted with a different input signal and no variation of the attachment and kinematic properties. This accustomed the subjects to the task and to the rating on the rating scales.

C. Statistical Design

Statistical hypothesis testing revealed the influence of the kinematic setting variation and attachment pressure variation to the individual scales of the subjective performance questionnaire, the dependent variables. Before ANOVA testing, all data vectors were successfully tested for normal distribution. Lilliefors testing was used for this, since it does not require a-priori knowledge of data mean and variance. In order to analyze all aspects of the results, a series of three 2-way ANOVA's were performed on each dependent variable of the experiment.

First, the influence of the kinematic condition on the dependent variable was tested (test: *T1*) by a 2-way ANOVA considering the kinematic condition as main and the subjects as secondary factor, with 6 repetitions per subject *(T1: n_{F1}=84, df_1=1; n_{F2}=12, df_2=13, rep.=6)*. Each repetition in this test relates to a different experiment run with different pressure setting. Next, the influence of the pressure variation was tested *(T2)* as main, with subjects as secondary factor *(T2: n_{F1}=28, df_1=5; n_{F2}=12, df_2=13, rep.=2)*. Here, two repetitions indicated that each pressure combination was tested with 2 experiment runs. To test the pressure variation independent of the variance contributed by the kinematic levels *(T3)*, two 2-way ANOVAs were performed for each dependent variable, with pressure condition as primary and subjects as secondary factor *(T3: n_{F1}=14, df_1=5; n_{F2}=6, df_2=13, rep.=1)*. Only significant results will be reported. Results on subject level proved to be too multifaceted and will not serve the purpose of this paper.

1) Independent Experiment Variables: The two primary independent factors are: (1) the kinematic condition with the two levels *'locked'* (*L*) and *'unlocked'* (*U*) and (2) the interface pressure *'I/F P'* with the six levels ranging from 10 – 60 mmHg. In some hypothesis tests also (3) the subjects were used as independent factor.

2) Dependent Experiment Variables: The dependent variables are (1) the comfort rating $\overline{C}$ that was acquired after each trial, (2) the group weighted total NASA TLX workload rating $\overline{W}_{WL}$, and (3 – 9) the group weighted ratings of the NASA TLX scales (*MD*, *PD*, *TD*, *OP*, *EF*, *FR*).

III. A BRIEF SUMMARY OF RELEVANT OBJECTIVE RESULTS

As reported in greater detail in [1], the analysis of objective measures of the experiment has shown that interface loads are significantly smaller if passive joints are free to move within the exoskeleton. Peak forces F_d for the group along the forearm were shown to range from -232 to 165 N for the *'locked'* and only from -57 to 70 N for the *'unlocked'* kinematic configuration. Constraint torques T_d imposed on the forearm attachment cuff by joint misalignments were shown to reach up to about 1.46 Nm for the *L* and only up to about 0.6 Nm for the *U* configuration. Furthermore, we had shown that these forces stem from misalignments between the exoskeletons elbow joint and the human arm's elbow joint and that such misalignments for the group were in the order of ± 10 cm in all directions. These offsets were created during the experiment runs, even though the exoskeleton was always visually aligned well prior to starting a trial.

Regarding the mean group RMS tracking error E^{Tr}, we had shown that it exhibits an interesting characteristic. Fig. 3 shows for clarity the resulting group tracking errors depending on kinematic and pressure variation. Results had been obtained with a similar statistical approach than presented in this manuscript. It was proven that for low attachment pressures, in the 10 – 30 mmHg region, tracking performance is better in the *unlocked* kinematic setting, whereas in the high attachment pressure region between 40

– 60 mmHg tracking performance was better for the *locked* kinematic configuration. We will be able to solve this observation in combination with the subjective results presented hereafter.

IV. Subjective Results

A. Comfort Questionnaire

1) Dependence on Attachment Pressure: The comfort questionnaire is sensitive to the interface pressure that has been applied at the fixation cuffs. *T2* revealed that at least for one pressure increment, the comfort ratings were different for the subject group ($F_{CP}[5,85]=9.5,\ p<0.001$). Post-hoc testing revealed that at 60 mmHg the perceived comfort was lower than at all other pressure increments. In particular, the perceived comfort at 60 mmHg was lower than at 50 mmHg ($F_{CP50/60}[1,28]=7.88,\ p=0.009$) and with a more profound effect lower than at 10 mmHg ($F_{CP10/60}[1,28]=30.93,\ p<0.001$). Fig. 4 depicts the measured mean comfort ratings $\overline{C}$ for the group over the original scale. In Fig. 4 (a) boxplots are shown. In Fig. 4 (b) the mean values are shown along with their 95 % confidence interval. It can be seen in (a) that the group comfort ratings decrease over increasing fixation pressures.

2) Dependence on Kinematic Configuration: There is only a weak influence on the comfort ratings from the variation of kinematic parameters. Testing for influence of the kinematic setting over specific pressures *(T3)* revealed that at 30 mmHg, the subjects rated the perceived comfort higher in the *U* configuration than in the *L* configuration ($F_{CPLU30}[1,13]=5.12,\ p=0.041$). However, despite being significant, this result seems to be not relevant. The highest overall group comfort rating was given for 20 mmHg in the *U* condition (Fig. 4 b).

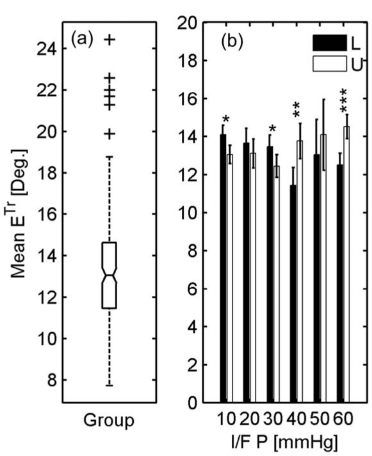

Fig. 3. Results of the group RMS tracking error E^{Tr} for the presented experiment. In (a) the overall tracking error for the subject group over all experiments is depicted. In (b), the overall group tracking errors are depicted for various interface pressure increments I/F P and both kinematic conditions of passive joints *locked 'L'* and *unlocked 'U'*. *, p<0.05; **, p<0.01; ***, p<0.001.

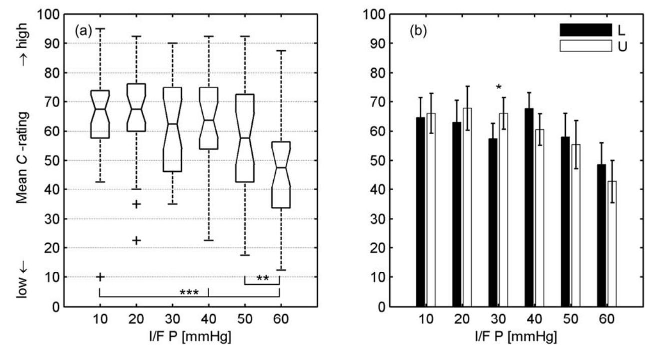

Fig. 4. Mean comfort rating $\overline{C}$ of the subject group is shown as boxplots over interface pressure *I/F P* in (a) and with 95 % confidence intervals over the kinematic setting (*'L'/'U'*)and pressure variation in (b). *, p<0.05; **, p<0.01; ***, p<0.001.

B. Preferred Attachment Pressure for the Group

When asked directly after the experiments, the subject group selected their preferred "most comfortable" interface pressure to be within 21.6 ± 8.7 mmHg for the upper-arm air-cuff and to be within 20.1 ± 7.7 mmHg for the forearm air-cuff.

C. NASA TLX Ratings

Following mean group weighting factors were determined for the NASA TLX rating scales after the experiment:

Mental demand *(MD)*:	1.93
Physical demand *(PD)*:	2.21
Temporal demand *(TD)*:	3.0
Performance *(OP)*:	2.71
Effort *(EF)*:	2.79
Frustration *(FR)*:	2.36

Analysis of the total perceived WWL scores $\overline{W}_{WL}$ did not reveal effects from the kinematic or pressure variation on total workload. The combined numeric value of the TLX is too coarse to be sensitive to the relatively small variations in the task elements. Considering the fact that the TLX index was developed for significantly more complex tasks, this is not a surprising finding. The effect of kinematic variation on the individual rating scales is shown in Fig. 5 (a), while the effect of pressure variation on the six individual rating scales is illustrated in Fig. 5 (b). In Fig. 5 (a) mean values along with the 95 % confidence interval are shown, whereas in (b) only the mean values are depicted for clarity.

1) Dependence on Kinematic Configuration: The kinematic setting variation of the exoskeleton shows a weak influence on one rating scale of the TLX index. *T1* confirmed that subjects experience less mental demand if the exoskeleton has passive joints to compensate misalignments of joint centers of rotation ($F_{MDLU}[1,140]=3.95,\ p=0.048$).

2) Dependence on Attachment Pressure: The pressure variation shows a more profound influence on the TLX ratings of the subjects (as in the comfort questionnaire).

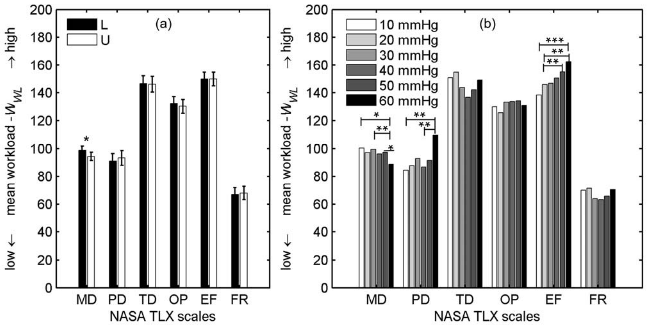

Fig. 5. Results of the subject group $\bar{W}_{WL}$ for the individual NASA TLX rating scales. In (a) influence of the kinematic setting variation on the scales is depicted by means with 95 % *CI* (*L*: *passive joints of exoskeleton locked, U: passive joints of the exoskeleton free to move)*. In (b) the influence of the attachment pressure variation from 10 – 60 mmHg is shown on the individual rating scale mean values. *, p<0.05; **, p<0.01; ***, p<0.001

T2 revealed effects of pressure variation on mental demand *(MD)* $(F_{MDP}[5,84]=2.46, p=0.04)$. Post-hoc testing (2-way ANOVA's with 2 pressure increments as main and subjects as second factor) revealed that perceived mental demand decreases towards higher pressures. With mental load experienced at 60 mmHg being lower than at 10, 30 and 50 mmHg *(All F[1,28]:* $F_{MDP10/60}=6.78$, $p=0.015$; $F_{MDP30/60}=9.21$, $p=0.005$; $F_{MDP50/60}=5.08$, $p=0.032$*)*.

Physical demand *(PD)* ratings are influenced by the pressure factor as well *(T2:* $F_{PDP}[5,84]=3.51$, $p=0.006$*)*. In particular, physical demand shows an increasing trend with higher pressures. Again, post-hoc tests confirmed higher physical demand ratings for 60 mmHg than for 10, 20 and 40 mmHg *(All F[1,28]:* $F_{PDP10/60}=10$, $p=0.004$; $F_{PDP20/60}=7.04$, $p=0.013$; $F_{PDP40/60}=8.84$, $p=0.006$*)*. This underlines nicely the trend that was found already in the comfort questionnaire, which postulates decreasing comfort at higher pressures.

The temporal demand *(TD)* as well as the operator performance *(OP)* does not show sensitivity to variation of the interface pressure.

The effort scale *(EF)*, hoever, showed again an effect induced by the pressure variation *(T2:* $F_{EFP}[5,84]=4.31$, $p=0.002$*)*. In particular, subjects rated effort higher at higher interface pressures. The post-hoc tests revealed that at 50 mmHg the subjects rate effort higher than at 10 mmHg, and that effort is higher at 60 mmHg than at 10 and 20 mmHg *(All F[1,28]:* $F_{EFP10/50}=10.1$, $p=0.004$; $F_{EFP10/60}=24.25$, $p<0.001$; $F_{EFP20/50}=8.85$, $p=0.006$*)*. These results seem to again underline the fact that lower pressures are more comfortable to the subjects. The question arises, whether the rating scales show congruent results with the deliberately chosen optimal pressure?

V. DISCUSSION

As apparent from the data, the interface pressure has a stronger influence on the subject's subjective performance metrics than the kinematic variation has.

When asked directly, the tested persons preferred to wear the exoskeleton at pressures between roughly 10 – 30 mmHg overall. Even though a large range of pressures was tested, the consciously chosen optimum pressure of the group lies within a relatively narrow range around 20 mmHg. It appears that this level of chosen pressure is also physiologically meaningful. The range of 10 – 30 mmHg might have less effect on muscular fatigue than the higher pressure range. However, we also see evidence for this choice in the subject's ratings on the various scales.

The mean subjective comfort ratings $\bar{C}$ peak at 20 mmHg in the *U (unlocked passive joints)* kinematic setting of the exoskeleton. This further consolidates a good optimum attachment pressure of about 20 mmHg. The weighting factors determined for the individual TLX rating scales show that the main workload of the task is associated with temporal demand, followed by effort. Temporal demand was not affected by either experimental factor. Effort rated by the human subject's shows to increase with higher pressures, as well as the physical demand of the task (Fig. 5 b).

But why, then, do the test persons not chose the lowest pressure for the task? It can be seen nicely that the choice is a trade-off between physical aspects and mental aspects of the task. The group preferred high pressures to reduce mental demand (Fig. 5 b). Nevertheless, as apparent in the task weighting factors, the other effects are more dominant, which is why, in summary the physical demand and effort caused selection of a lower interface pressure, at the expense of slightly increased mental demand. This indicates that the subjective choice of interface pressure followed a concise scheme or trade-off. The subjective ratings seem coherent and acceptable. At the same time, it can be seen from Fig. 3 that the choice of a low attachment pressure does not negatively affect the signal tracking performance, e.g. through causing slack or backlash in the system.

Considering now the kinematic setting as well, it is interesting to observe the results presented in Fig. 3. We can see in Fig. 3 (b) that the same subjects experienced better signal tracking behaviour (less RMS tracking error) in low cuff pressures, if the kinematic setting of the exoskeleton was in *unlocked* condition, which also exhibited less interface loads F_d and T_d. Moreover, the subjects experienced better signal tracking behaviour in high pressure fixation, if the kinematic setting of the exoskeleton was in *locked* condition, that generally exhibited more interface forces. Thus, the overall preference could adapt to two states, everything loose or everything stiff. In short, we could hypothesize that humans prefer a coherent design and setting for the exoskeleton device.

Knowing from the results presented herein that the optimum conscious choice is about 20 mmHg, we can then select the *unlocked* passive joint configuration as further optimum, since it aids in tracking performance, according to Fig. 3 (b).

Yet, if we consider our preferred selection with *unlocked* passive joints and low cuff pressure, we see that also the mental demand ratings are positively affected by the choice of kinematic configuration Fig. 5 (a).

In general, cuff pressure variation shows more effect on the subjective measures in our tracking experiment, whereas the kinematic variation shows more effect on the objective measures presented in [1]. Despite the high forces that were created by the *locked* kinematic setting, the subjects did, with the exception of mental load, not clearly perceive the differences in kinematic setting. It appears that the pressure variation in this experiment was the more dominant influence on subjective measures, dominated by comfort, effort and physical demand. Nevertheless, we have shown that a combination of low cuff pressure and enabling of passive compensation joints will lead to a comfortable exoskeleton setting, without altering signal tracking performance.

It will be interesting, in the future, to put the results into perspective. Certainly, the experiments presented here should be conducted again, without variation of interface pressure to make the subjective metrics more sensitive to the kinematic setting variation. We will need to investigate how the differences of interface loads in *U* and *L* seetings will be subjectively experienced in a fully actuated exoskeleton. In particular for applications, where force-perception with high resolution and dynamic range is critical, e.g. in haptic devices, the inclusion of passive compensatory joints might further improve the feel and mechanical transparency of the device. For such systems, a linear force characteristic would be ideal, with as little disturbance as possible stemming from mechanical mis-matches. With regard to the level of typical force-feedback loads applied to the human joints, which are typically in the order of 1/20th of the maximum human joint strength, the elimination of high interface forces with passive joints seems attractive. (As an example, the exoskeleton presented in [13] transfers a torque of 6 Nm to the elbow. The exoskeleton from [2] can apply a force of 50 N cont. or 100 N peak to the tip of the hand). For robots that transfer large forces and torques, such as e.g. rehabilitation robots, the inclusion of compensation joints might even reduce safety critical peak loads.

We can summarize that low attachment pressures (20 mmHg ideally), along with the unlocked kinematic setting of the exoskeleton appears to be an optimal trade-off for comfort and other subjectively experienced performance metrics. We can state that this choice of conditions is also good for signal tracking performance and low constraint force loading onto the human arm by wearable robots.

VI. Conclusion

(1) The influence of attachment pressure on subjectively perceived comfort was shown to be more dominant than the influence of kinematic setting variation and interface load. (2) Comfort increases with lower attachment pressures. (3) The optimum interface pressure between exoskeleton and human arm, from a subjective point of view is 20 mmHg on upper-arm and forearm attachment cuffs. (4) Objective performance does not worsen with this. (5) The best combination of subjective and objective performance for the task can be reached by an ergonomic exoskeleton with passive compensation joints that is attached with the optimum attachment pressure.

References

[1] A. Schiele, "Ergonomics of Exoskeletons: Objective Performance Metrics," in 3rd joint World Haptics Conference (WHC), Salt Lake City, UT, 2009, pp. 103 – 108.

[2] A. Frisoli, F. Rocchi, S. Marcheschi, A. Dettori, F. Salsedo, and M. Bergamasco, "A New Force-Feedback Arm Exoskeleton for Haptic Interaction in Virtual Environments," in Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. First joint World Haptics Conference, Pisa, 2005, pp. 195-201.

[3] A. Schiele, M. D. Bartolomei, and F. v. d. Helm, "Towards Intuitive Control of Space Robots: A Ground Development Facility with Exoskeleton," in IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Beijing, 2006, pp. 1396-1401.

[4] A. Zoss and H. Kazerooni, "Design of Electrically Actuated Lower Extremity Exoskeleton," Advanced Robotics, vol. 20, pp. 967-988, 2006.

[5] R. Riener, T. Nef, and G. Colombo, "Robot-aided neurorehabilitation of the upper extremities," Medical and Biolocial Engineering and Computing, vol. 43, pp. 2-10, February 2005 2005.

[6] R. Alami, A. Albu-Schaeffer, A. Bicchi, R. Bischoff, R. Chatila, A. D. Luca, A. D. Santis, G. Giralt, J. Guiochet, G. Hirzinger, F. Ingrand, V. Lippiello, R. Mattone, D. Powell, S. Sen, B. Siciliano, G. Tonietti, and L. Villani, "Safe and Dependable Physical Human-Robot Interaction in Anthropic Domains: State of the Art and Challenges," in presented at: IEEE International Conference on Intelligent Robots and Systems Beijing, China: IEEE, 2006.

[7] A. Schiele, "Fundamentals of Ergonomic Exoskeleton Robots." vol. Ph.D. Thesis Delft: Delft University of Technology, 2008, available at: www.library.tudelft.nl

[8] G. Colombo, M. Joerg, and V. Dietz, "Driven gait orthosis to do locomotor training of paraplegic patients," in International Conference of the 22nd Annual EMBS, Chicago, IL, USA, 2000, pp. 3159-3163.

[9] J. M. Hidler and A. Wall, "Alterations in Muscle Activation Patterns during Robotic-assisted walking," Clinical Biomechanics, vol. 20(2), pp. 184-193, 2005.

[10] N. D. Neckel, D. Nichols, and J. M. Hidler, "Joint Moments Exhibited by Chronik Stroke Subjects While Walking with a Prescribed Physiological Gait Pattern," in IEEE 10th International Conference on Rehabilitation Robotics, Noordwijk, Netherlands, 2007, pp. 771-775.

[11] A. Schiele and F. v. d. Helm, "Kinematic Design to Improve Ergonomics in Human Machine Interaction," IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 14(2), pp. 456-469, 2006.

[12] A. Schiele, “Case Study: The ergonomic EXARM Exoskeleton”, in *Wearable Robots: Biomechatronic Exoskeletons*, J.L. Pons Ed., John Wiley & Sons, pp. 248-255, 2008

[13] S. G. Hart and L. E. Staveland, "Development of the NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research," in Human Mental Workload, P. A. Hankock and M. Meshkati, Eds. North-Holland: Elsevier Science, 1988, pp. 139-182.

[14] N. G. Tsagarakis and D. G. Caldwell, "Development and Control of a "Soft-Actuated" Exoskeleton for Use in Physiotherapy and Training," Autonomous Robots, vol. 15, pp. 21-33, July 2003.