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The relationship between prescribed ratings of perceived exertion and force production in repeated isometric contractions

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ABSTRACT

Ratings of perceived exertion (RPE) are frequently used to monitor and prescribe exercise intensity. However, studies examining the shape and robustness of how feelings of effort map onto objective outputs are limited and report inconsistent results. To address this, we investigated whether (1) producing isometric forces according to RPE levels reliably leads to differences in force output, (2) if feelings of effort map linearly or non-linearly onto force output, and (3) if this mapping is robust when visual feedback and social facilitation are present. In a counterbalanced repeated measures design, $N = 26$ participants performed isometric handgrip contractions prescribed by ten levels of the Borg CR-10 scale. They did so either with or without the availability of concurrent visual feedback regarding their force production, and in the presence or absence of another person performing the same task simultaneously. We found that subjects reliably produced different force outputs that corresponded to each RPE level. Furthermore, concurrent visual feedback led to a linearization of force output, while in the absence of feedback, the produced forces could also be described by quadratic and cubic functions. Exploratory post-hoc analyses revealed that participants perceived moderate RPE levels to be more challenging to produce. By shedding light on the dynamic nature of the mapping between RPE and objective performance, our findings provide helpful insights regarding the utility of RPE scales.

1. Introduction

Ratings of perceived exertion (RPE) are routinely used by researchers and practitioners to assess a person's experience of investing effort in physical tasks (Chen et al., 2002; Kasai et al., 2021). These ratings are typically assessed via scales ranging from 0 to 10, 6 to 20, or 0 to 100 (Borg, 1970, 1982; Borg & Borg, 2002). Research has shown that the perception of effort is associated with several physiological parameters, such as heart rate and lactate levels (Mays et al., 2010; Scherr et al., 2013), as well as performance indicators, such as running speed and movement velocity (Helms et al., 2017; Rago et al., 2020; Rotstein et al., 2005). Consequently, RPE measures yield valuable information that can be used in clinical and performance settings (Inoue et al., 2022; Mays et al., 2010).

In general, coaches and trainees can utilize RPE ratings in one of two ways: monitoring or prescription. With monitoring, trainees perform a physical task and report their RPE at specific intervals. For instance, a person may run on a treadmill at a predetermined speed and report their RPE every 3 min. Conversely, in terms of prescription, trainees can be directed to perform a physical task at a predetermined RPE value. In this case, a runner's instruction could be to run at a speed corresponding to an RPE value of 8 out of a possible 10.[1] Both variants have been shown to provide valuable and actionable strategies across a range of populations and exercise modalities (Alsamir Tibana et al., 2019; Boxman-Zeevi et al., 2022; Garnacho-Castaño et al., 2018; Glass et al., 1992; Ormsbee et al., 2019; Row Lazzarini et al., 2017; Tiggemann et al., 2021).

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[1] We used examples from endurance training because of their frequent use, but the principles of RPE-based monitoring and prescription also apply to resistance training. However, using repetitions and sets can lead to more variation in how RPE ratings are employed. For instance, with prescription, RPE ratings can be used in combination with repetitions in reserve (Zourdos et al., 2016) or open and closed repetitions (Boxman-Zeevi et al., 2022). With monitoring, an entire exercise session or singular sets of an exercise can be rated (Day et al., 2004; Helms et al., 2016).

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Importantly, the majority of studies have investigated the validity and utility of RPE in the context of monitoring, and fewer studies have investigated RPE in prescription contexts (Chen et al., 2002; Lea et al., 2022). In this study, we will address three key open questions with respect to RPE in prescription contexts.

First, to maximize the potential utility of RPE as a tool for prescription, it is crucial to understand how prescribed RPE levels map onto observed performance. Simply put, it must be clear whether prescribing different RPE levels reliably leads to equivalently different force outputs. Recent studies have addressed this question by asking participants to produce four (Li & Yu, 2011; Rewitz et al., 2023) or five (Hampton et al., 2014; John et al., 2009) different RPE levels of the Borg CR-10 scale. While most studies found that the produced forces differed across all prescribed levels, Hampton et al. (2014) only observed differences in force output between three out of the five levels. Adopting a more fine-grained approach, Pincivero (2011) investigated torque production in a knee extension task across all ten levels of the CR-10 scale. Their data revealed a significant main effect for torque produced by RPE level, which is consistent with prior work that yielded similar findings (Pincivero et al., 2003b). Due to a different research focus, no post-hoc comparisons were done between the prescribed RPE levels (e.g., comparing torque at RPE 4 to torque at RPE 5), leaving open the question of how fine-grained subjective differences in RPE translate to objective differences in force. Taken together, if only a few broadly spaced RPE levels have to be produced (e.g., 2, 4, 6, and 8), the observed force output seems to differ accordingly. Only one study showed slightly different results (Hampton et al., 2014), as not all differences reached statistical significance (there was a descriptive difference between the remaining levels). However, it is currently unclear if the differences in force output also hold true when more levels of an RPE scale are used. Thus, to understand the mapping between RPE production and observed performance, it is imperative to use the full RPE scale and to test for the order and magnitude of differences between each level.

Second, beyond mere ordinal differences between produced RPE levels and observed performance, it is important to understand the shape of the RPE-performance mapping across the full RPE scale (Rewitz et al., 2023). In the original Borg RPE scale (Borg, 1970, 1982), the 6–20 ratings are thought to correlate with heart rate (with 6 equaling ~ 60 bpm, 7 equaling ~ 70 bpm, etc.), and the levels increase in constant intervals, assuming a linear progression. This assumption is also underlying the Borg category-ratio (CR-10) scale (Borg, 1982), where the steps represent increases of the same size. If the relationship between effort ratings and exercise output would not be linear across the full scale, the derivations for prescribing exercise intensity would not be consistent. That is, increases in RPE would map unproportionally onto actual exercise output. To exemplify, let us assume a perfectly linear progression where force output increases steadily with RPE. At a prescribed level of RPE 4 out of 10, the force output from an exerciser would be, let's say, 40 N, while at RPE 8, it would be 80 N. Now, if the shape of the RPE-performance mapping would exhibit a quadratic (i.e., convex) pattern, the hypothetical output might rather correspond to 30 N at RPE 4 and 70 N at RPE 8. This would mean that the prescribed RPE would not lead to the intended performance, and this misalignment might even be different across effort levels. These inconsistencies can potentially hinder desired training adaptations, as different training loads elicit different physiological responses. Few studies have investigated the shape of the mapping between RPE and produced force with heterogenous results, as both linear and non-linear associations have been reported (Cochran et al., 2007; Li & Yu, 2011; Morrin et al., 2018; Pincivero, 2011; Rewitz et al., 2023). To illustrate, in some studies, a linear increase in RPE mapped onto a linear increase in the produced force (Li & Yu, 2011; Morrin et al., 2018), whereas in other studies, a linear increase in RPE led to both linear and quadratic increases in the produced force (Cochran et al., 2007; Pincivero, 2011; Rewitz et al., 2023). The inconsistencies between studies are potentially due to differences in the implemented tasks (e.g., handgrip squeeze vs. knee extension), contraction and rest durations (Diniz et al., 2014; Farah et al., 2012), and the number of prescribed RPE levels, which ranged from four to ten in the aforementioned studies. Clearly, the shape of the RPE-performance relationship is far from understood, and research that investigates this shape across the full effort scale is scarce.

Third, the alignment between RPE and performance might not be the same across situations and vary due to psychological factors. For example, it is well established that psychological factors such as performing in front of a crowd or listening to music can influence performance (Ballmann et al., 2021; Rhea et al., 2003). Beyond performance, factors such as self-efficacy or attentional focus can also impact the perception of effort (Hutchinson et al., 2008; Tenenbaum & Connolly, 2008). Building upon these insights, we will focus on two psychological factors that might affect the RPE-performance mapping in prescription contexts: the presence of others (i.e., social facilitation) and augmented visual feedback (i.e., concurrent visual feedback on force production).

People often exercise in a social environment in which training partners, coaches, or other exercisers are present. Based on the effect of social facilitation (Zajonc, 1965), the presence of another person performing the same task as oneself can lead to an increase in performance (i.e., the co-action effect). On a similar note, the presence of one or more passive bystanders can wield notable influence. Baker et al. (2011) have shown that the mere presence of two observers can increase the lifted weight in a leg and bench press task. Similarly, research has shown that the presence of a spotter is associated with increased performance in bench presses, while also reducing RPE and increasing ratings of self-efficacy (Sheridan et al., 2019). Adding to the social influence on force production, it has been shown that an audience can lead to enhanced performance in different strength tasks (Rhea et al., 2003). Leitzelar et al. (2016) tested whether RPE ratings differ in a handgrip task that is performed with a small audience (four members) vs. a control group. They found that RPE did not differ significantly between the two groups. However, the audience group lasted longer on task (i.e., they performed more repeated contractions at 30 % MVC until reaching RPE 10/10). This is in line with a study by Carnes et al. (2013), who found no differences in RPE during a self-paced submaximal treadmill exercise that was performed with a peer or alone. Overall, the presence of others has demonstrated a positive impact on performance in different strength-based tasks and in different social settings (i.e., one or more people being present). However, the relationship between social facilitation and RPE is not fully clear and demands further investigation.

With respect to concurrent visual feedback, several studies have linked visual feedback to increased performance in strength-based tasks. For instance, concurrent visual feedback has been shown to positively influence performance in handgrip contractions, jumps, or leg extensions (Ekblom & Eriksson, 2012; Fischer et al., 2010; Marcel-Millet et al., 2021; Wilson et al., 2018). However, research on the connection between visual feedback and RPE is scarce. Wilson et al. (2017) assessed the influence of visual feedback in a back squat exercise while also assessing RPE. They not only found improved performance in the feedback condition compared to the no feedback condition, but also differences in effort ratings between the conditions. On average, the effort ratings were higher in the feedback condition.[2] Interestingly, the authors further found increased levels of motivation and competitiveness when feedback was available, which they considered a potential explanation for the performance increase. Supporting this effect of concurrent visual feedback, this finding has been replicated in other studies (Weakley et al., 2019; Wilson et al., 2018).

In summary, both factors (i.e., the presence of others and augmented visual feedback) have been shown to positively impact performance in

[2] It should be mentioned that the authors did not use a typical RPE scale in their study. They used Hart and Staveland's NASA Task Load Index (TLX), which includes the question "How hard did you have to work to accomplish your level of performance?" as a proxy of effort.

resistance-based tasks and have been linked to changes in RPE. Studies that have investigated if and how the variables affect the mapping between RPE and force in prescription contexts are lacking. However, this is a crucial question from an applied and theoretical perspective. With respect to the former, it matters to know if variables such as the presence of others or concurrent visual feedback alter an exerciser's prescribed training intensity. With respect to the latter, it is particularly interesting to see if factors that are known to improve performance would alter the RPE-performance relationship. This is interesting because, in this context, achieving higher performance (i.e., producing more force at a specified level) does not necessarily mean better performance. Instead, it suggests that how our subjective feeling of effort affects objective performance depends on the context.

1.1. The present research

Taken together, we study three key questions about RPE-performance mapping in a prescription context. First, we investigate to what extent prescribing different RPE values will correspond to different force outputs. Second, we aim to determine the specific shape of the RPE-performance mapping. Third, we examine the influence of social facilitation and visual feedback on this mapping. We address this research gap with a counterbalanced within-subjects experimental study with isometric grip force as the exercise modality. We expect a monotonous increase in force output when the prescribed RPE level increases. We further expect that real-time feedback will lead to a more robust mapping between RPE and force because participants can use external feedback to adjust their performance. With respect to social facilitation, we expect that the presence of others will lead to higher force output across all RPE levels. Finally, with respect to the shape of how a linear increase in RPE level would map onto the force output, we adopt an exploratory approach, as the available literature is limited and heterogeneous.

2. Methods

2.1. Participants

A total of 26 participants (19 men and 7 women, age = 23.2 ± 1.7 years) took part in the study. A G*Power analysis (Faul et al., 2007) was performed to estimate the required sample size (ANOVA; repeated measures, within factors). It revealed that in order to detect differences with a statistical power of 95 %, an alpha level of 0.05, and an effect size of $f = 0.25$, a sample size of $N = 20$ participants would be sufficient. As there is no prior research to base our effect size estimation on, we targeted a sample size that would allow us to detect at least a moderate sized effect with high statistical power (Cohen, 1988). People with acute injuries or any impairment to their dominant arm were not allowed to participate in the study. The participants were recruited as part of an undergraduate seminar. All participants read and signed an informed consent before the experiment. The measurements were conducted at the Sport Psychology Laboratory at the University of Konstanz in accordance with the principles of the Declaration of Helsinki.

2.2. Experimental design

The experiment was set up as a 2 (feedback vs. no feedback) x 2 (alone vs. together) x 10 (RPE levels) within-subject design. To be able to look at main effects as well as potential interaction effects, we used a combination of the 2x2 factors, resulting in four conditions: I) alone, with feedback, II) alone, without feedback, III) together, with feedback, IV) together, without feedback. The ten-level factor (RPE levels) was nested into the measurement cells (i.e., conditions) as levels of prescribed force. Over the course of four weeks, the study participants performed one session based on one measurement cell each week, in a randomized (the RPE levels) and counterbalanced (the four conditions) order. An experimental session consisted of two measurements of maximum voluntary contraction (MVC-pre), followed by the main handgrip task (i.e., contractions according to RPE levels), and finally, two additional measurements of MVC (MVC-post).

2.3. Procedure

On each measurement day, participants were instructed on their tasks by the experimenters before starting. The session proceeded with the MVC-pre measurements, which were separated by a 30-s break. Here, participants were instructed to exert as much force as possible on a grip force transducer for 3 s. In the main task, participants produced forces prescribed by ten levels of the Borg CR-10 scale, with "one" meaning very weak effort and "ten" meaning maximum effort (Borg, 1982). The instruction was to exert as much force on the handgrip transducer as the effort level prescribed. For example, "level four" would represent a handgrip contraction that corresponds to an effort rating of four on the RPE scale (meaning a force production that "feels" like a four to the participant). For the force production task, the instructions were given by a computer. Here, each level was announced with an audio signal (e.g., "level four"), which was followed by a start signal after 2 s. Beginning with the start signal, force was exerted until a distinct stop signal was audible. Each handgrip contraction lasted for 5 s. All of the levels (1–10) were performed twice, and the order of the required contractions was randomized, totaling 20 force productions. The rest period between the contractions was set to 10 s. After the main task, MVC (post) was assessed again with a 30-s break in between the two maximum contractions. After completion of all measurement days, participants completed an online questionnaire for demographic information, as well as two exploratory questions on self-perception and performance. These questions ("How accurate did you feel you were able to exert force in each measurement session?" and "How accurate did you feel you were able to exert force for each level?") were answered on an eleven-point Likert-type scale ranging from 0 (not at all) to 10 (extremely accurate). One participant did not fill out the online questionnaire.

2.4. Setup of the handgrip measurements

The participants performed the experiment in a seated position, and body posture was standardized by implementing a 90° knee angle and a 90° elbow angle through seat and elbow-rest adjustments. Study participants used the force transducer in their dominant arm and were instructed to keep the device in a vertical position and to avoid unnecessary bodily movement during contractions. The participants were instructed not to interact with other participants or the experimenter during the trials. Concurrent visual feedback was implemented by placing a computer screen in front of the participants, on which they could see their produced force in a real-time graph.[3] Based on the designated measurement cell, the participants either faced the computer screen in front of them so that concurrent feedback was visible or turned their back to the screen so that feedback was not available. Social facilitation was implemented by having two participants perform the exact same task while sitting next to each other and using two separate handgrip transducers. Thus, the prescribed RPE levels as well as the contraction and rest durations were identical for both participants. In measurements where feedback and social facilitation were combined, two separate force graphs were depicted on the screen. To standardize auditory input, general instructions were given by one experimenter, and the force production task was guided by computer signals.

[3] The force output was visible as a line graph, where the y-axis displayed Newtons (N) in steps of 100 N (with dotted lines at every 25 N). The x-axis showed time in seconds.

2.5. Instruments

To measure isometric handgrip strength, a MLT004/ST grip force transducer (AD Instruments, New Zealand) was used. It was calibrated to zero by the experimenters before each measurement trial. Signals for the respective RPE levels were produced using the NIRStim software (NIRx Medical Technologies LLC, USA) and combined via a Cedrus StimTracker (Cedrus Corporation, USA) with the Powerlab signal acquisition hardware and the LabChart software (AD Instruments, New Zealand) for data collection. The force output was measured in Newton (N). As per the default settings of the data-acquisition software (LabChart), the force signal was sampled at 1000 Hz (i.e., 1000 data points per second). In a later step, the resulting dataset was reduced in size for data handling. This was done by down-sampling it by a factor of 20, resulting in 50 data points per second.

2.6. Statistical analyses

Regarding the MVC measurements, the peak value from the two contractions was used for analysis. The force exerted at each RPE level was calculated by taking the mean value of the last 4 s of the 5-s-long isometric contraction to account for a slight delay in force production that was visible after reacting to the audio command. Data processing was completed using the software R (Version 4.2.2) and JASP (Version 0.16.1).

To test if the produced force differed between factors, a Linear Mixed Model was used. The model fitted fixed slopes for the variables "feedback" (with, without), "social facilitation" (alone, together) and "RPE level" (1–10) and random intercepts for each participant ("ID"). We performed the main analysis with the *lme4* (version 1.1–29) and *lmerTest* (3.1-3) packages in R (Bates et al., 2015; Kuznetsova et al., 2017). Post-hoc comparisons were corrected through the Bonferroni-Holm method. Further, polynomial contrasts were calculated to identify potential trends in the data. By "trends," we mean if the force output could be modelled using linear, quadratic, cubic, or quartic functions. In addition, we conducted a repeated measures ANOVA (rmANOVA) that included time (pre, post), social facilitation (alone, together), and feedback (with, without) as factors to assess if MVCs would also be subject to variation. This analysis was an explorative post-hoc analysis and not part of our initial research question. As a second exploratory post-hoc analysis, we conducted Friedman's test to assess if participants' confidence in having accurately translated their RPE into the required force differed between conditions and across RPE levels.

3. Results

Descriptive statistics for the overall force output are provided in Table 1.

3.1. Main results

Testing the differences in force production, the Linear Mixed Model revealed a significant main effect for feedback ($F(1, 975) = 124.15$, $p < 0.001$, $\eta_p^2 = 0.11$), as well as for social facilitation ($F(1, 975) = 48.07$, $p < 0.001$, $\eta_p^2 = 0.05$), indicating that the average force output differed significantly depending on whether feedback was available or not, and whether another person was present during the task or not. A significant main effect was also found for RPE-level ($F(9, 975) = 894.54$, $p < 0.001$, $\eta_p^2 = 0.89$), where post-hoc analysis revealed that on average, all levels (1–10) showed significantly different force outputs ($p < 0.001$ for all comparisons; RPE 1 to RPE 2, RPE 2 to RPE 3, etc.) (Figure 1). Furthermore, a significant interaction effect between feedback and social facilitation was found ($F(1, 975) = 11.16$, $p < 0.001$, $\eta_p^2 = 0.01$), showing that combining feedback and social facilitation increased the average force output (Table 1). Lastly, a significant interaction effect was found between feedback and RPE-level ($F(9, 975) = 6.86$, $p < 0.001$, $\eta_p^2 = 0.06$), indicating that depending on the availability of feedback, force output differed within levels. No significant interaction effect was found between social facilitation and RPE level ($p = .93$).

Table 1
Overview of the produced average forces (±SD) in Newton and as a percentage of MVC (±SD).

Variable	Alone, with feedback	Alone, without feedback	Together, with feedback	Together, without feedback
Mean Force (N)	168.0 (±105.23)	137.86 (±91.29)	180.77 (±103.56)	168.0 (±98.40)
Mean Force in %MVC	38.97 (±21.57)	32.77 (±20.83)	40.50 (±20.96)	37.16 (±20.35)

In addition, post-hoc analyses revealed that with concurrent feedback, participants produced different force outputs for all levels, with all pairwise comparisons (RPE 1 to RPE 2, RPE 2 to RPE 3, etc.) indicating statistically significant differences (all p's < 0.001). Surprisingly, also without feedback, pairwise comparisons showed significant differences for all levels (all p's < 0.01), indicating that people's feelings of effort were reliably transposed into distinguishable outputs. This indicates that different subjective experiences (i.e., differences in RPE) lead to the respective ordinal difference in objective force output.

To determine whether the produced forces followed a linear pattern (as implied in RPE scales) or could better be described with non-linear shapes, we performed polynomial contrasts for the four measurement cells. When feedback was available and subjects were alone, only a linear comparison was significant ($t(225) = 59.28$, $p < 0.001$). Similarly, a linear trend was found when feedback was available and another person was present ($t(225) = 62.80$, $p < 0.001$). Interestingly, when no feedback was available and subjects performed the task alone, linear comparisons ($t(225) = 52.06$, $p < 0.001$) as well as quadratic ($t(225) = 10.36$, $p < 0.001$) and cubic ($t(225) = 4.76$, $p < 0.001$) comparisons reached significance. Lastly, without feedback and the presence of another person, linear ($t(225) = 49.14$, $p < 0.001$), quadratic ($t(225) = 5.59$, $p < 0.001$) and cubic ($t(225) = 2.75$, $p < 0.01$) comparisons reached significance. This shows that whereas feedback appears to linearize the process of transposing feelings of effort into objective performance, being fully reliant on one's sensations leads to patterns that also consist of non-linear elements.

3.2. Exploratory post-hoc analyses

In light of the effects the experimental conditions seemed to have on the relationship between RPE and produced forces, we conducted an unplanned exploratory post-hoc analysis to assess if MVC too varied as a function of experimental condition. Here, descriptive statistics revealed that on average, the produced force resulted in 439.96 N (±93.47) before the main task, compared to 372.87 N (±83.46) after the main task. A repeated measures ANOVA revealed a significant main effect for time ($F(1, 25) = 89.74$, $p < 0.001$, $\eta_p^2 = 0.78$), indicating an effect of exhaustion. A significant main effect was also found for social facilitation ($F(1, 25) = 10.66$, $p < 0.01$, $\eta_p^2 = 0.30$), with post-hoc analysis revealing that performing the MVC-measurements in the presence of another participant led to a higher average force output compared to when done alone ($t(25) = -3.26$, $p < 0.01$). No significant main effect for feedback was found ($p = .19$), and no significant interaction effect between the factors was found ($p = .46$).

As a second exploratory post-hoc analysis, we assessed participants' self-assessed accuracy in producing the required force. To this end, participants indicated how accurately they felt they had produced a force that reflected their RPE at each level and for each condition. Compared to the conditions with feedback (alone: 7.64 ± 1.50; together with another person: 7.72 ± 1.06), self-assessed accuracy in the conditions without feedback was lower (alone: 4.64 ± 1.63; together with another person: 4.68 ± 1.68). A Friedman's test revealed a significant

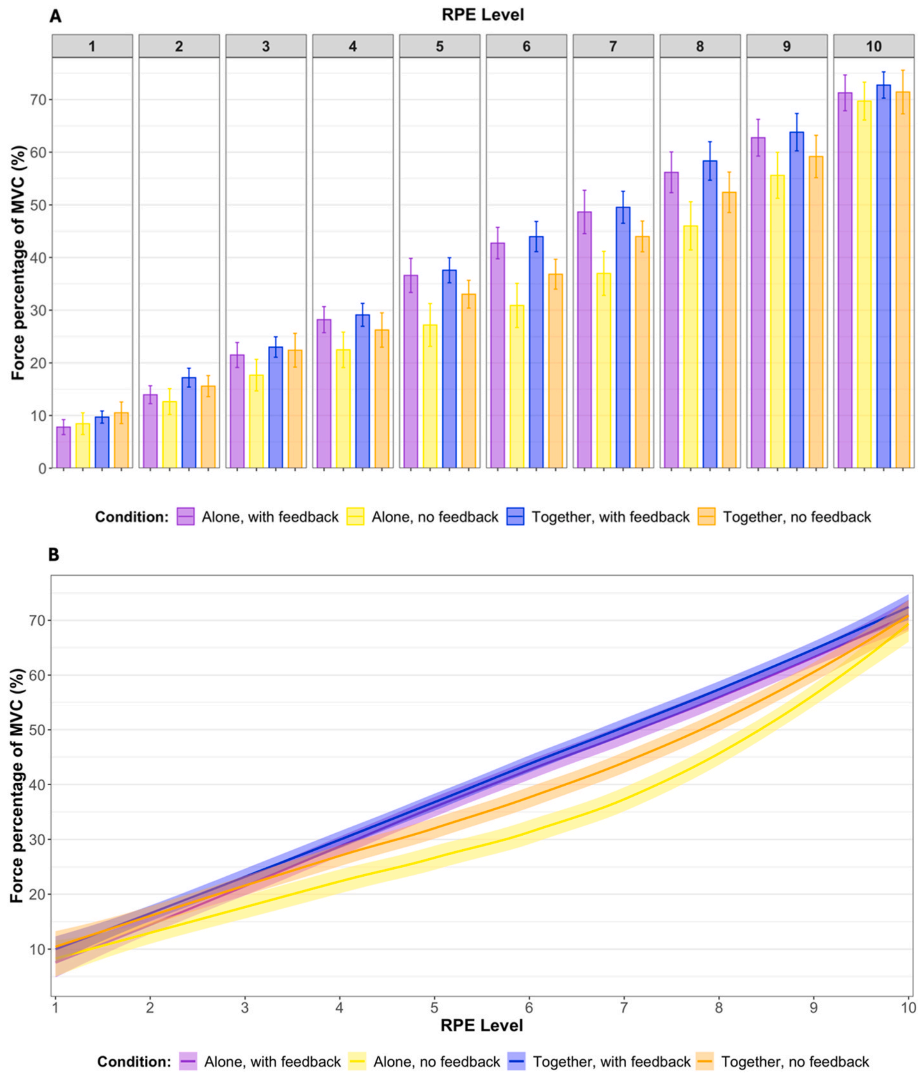

Figure 1. Visualization of the produced forces as a function of feedback (with feedback vs. no feedback) and social facilitation (alone vs. together) for all RPE levels. Panel A shows the average produced forces by condition and RPE level. The error bars represent the standard error of the mean. Panel B represents locally estimated scatterplot smoothing (with a 95 % CI), indicating the linear mapping in conditions with feedback and the more convex pattern in conditions without feedback.

difference between the ratings ($\chi^2(3) = 59.20, p < 0.001$). This indicates that people were less convinced about how accurately their perception of effort reflected objective force when they could not rely on external feedback. Lastly, in the second question, we asked how accurately subjects felt they were able to produce force for each level (0: not at all, 10: extremely accurate). A Friedman's test revealed a significant main effect for the ratings of the ten levels ($\chi^2(9) = 58.85, p < 0.001$). It was shown that participants found it increasingly difficult to do so up to level 7, after which the rating rose again (Figure 2).

Lastly, we performed an exploratory post-hoc analysis of individual performances. Descriptive statistics shows that in most cases (+80 %), people indeed produced higher forces at higher RPE levels (Figure 3). The percentage tends to vary as a function of the RPE level people were asked to produce and as a function of the availability of feedback. Interestingly, the variation in the percentage of successful individual level force production is consistent with the variation in self-reported confidence in accurately producing the required force.

4. Discussion

Here, we investigated how individuals perceive their feelings of effort (based on prescribed levels of RPE) and convert them into force output (i.e., how many Newtons of force are generated). We investigated this process across ten levels of RPE and did so with or without concurrent visual feedback, as well as with or without another person performing the task at the same time. With respect to our primary research questions, our study yielded three main findings: First, producing force at higher subjective effort levels robustly translated to higher force outputs. The exerted forces differed significantly (and in the expected direction) between all ten RPE levels, irrespective of the condition. Second, we found that the shape of the mapping between prescribed RPE levels and produced force was not always fully linear. In the feedback conditions, higher RPE levels led to a linear increase in the produced forces. However, in addition to linear contrasts, quadratic and cubic contrasts were significant in the no-feedback conditions. To illustrate, we found that the force output at lower RPE levels (e.g., RPE 1–4) increased with a shallower slope compared to the higher RPE levels (e.g., RPE 7–10) in the no feedback conditions. Therefore, equivalent differences in subjective effort did not lead to equivalent differences in force production across the full RPE scale. Third, we found that the average force that is produced across RPE levels varies as a function of feedback and social facilitation (i.e., the presence of others). We also found a significant interaction effect between the two factors, in which force increased when both feedback and another person were present.

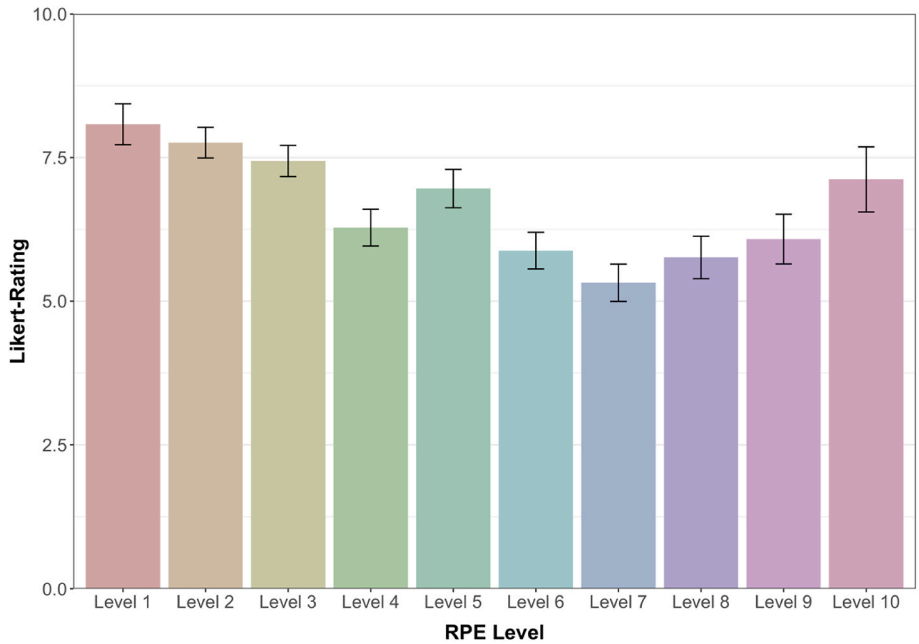

Figure 2. Visualization of self-reported confidence in accurately producing the force that represents the respective RPE levels. The question did not include information about feedback or social facilitation but was asked irrespective of these factors. The error bars represent the standard error of the mean.

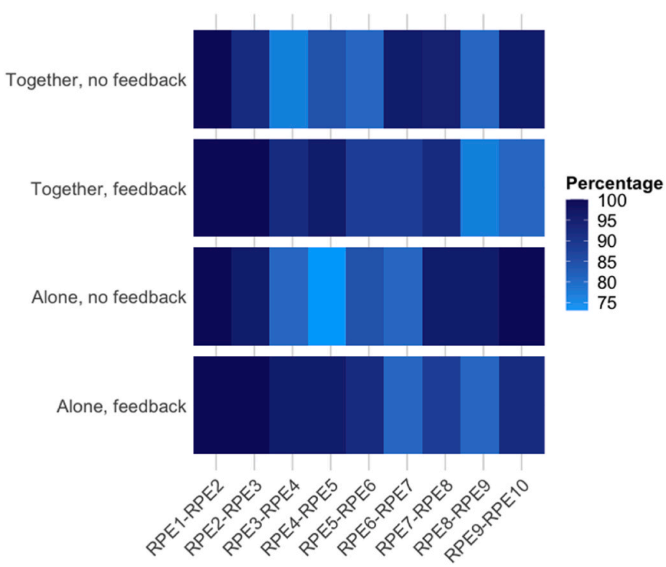

Figure 3. Visualization of force differences between adjacent RPE levels as a function of feedback (with feedback vs. no feedback) and social facilitation (alone vs. together) for all RPE levels. The percentage represents the proportion of participants who produced higher forces at adjacent RPE levels (e.g., RPE 1 was lower than RPE 2). The figure shows that participants produced the expected force differences at very high rates (75 % and above). Interestingly, accuracy seemed to vary as a function of RPE level and condition, and the descriptive pattern coincides with ratings on the self-assessed accuracy. These indicated that participants tended to have a harder time to differentiate effort levels in the middle part of the scale. This was particularly pronounced in conditions without feedback.

To illustrate, the largest force output was produced when another person was present and feedback was available, and the lowest amount of force was exerted when subjects performed the task alone and without visual feedback.

In addition to these main findings, we conducted exploratory post-hoc analyses. The first analysis revealed that MVC values were higher when another person was present. This highlights that even measures that are deemed maximal — and that are frequently used to standardize task demands — vary as a function of psychological variables. In a second exploratory analysis, we found that participants found it more difficult to produce the force they felt was accurate when they had to rely on their internal sensations only (i.e., no feedback) and when the to-be-produced RPE levels were moderate. The latter finding is especially interesting, as it highlights that not all RPE levels feel equally difficult, thereby introducing a source of variance into the relationship between RPE and performance. Lastly, we showed that on an individual level, participants produced distinguishable force outputs for the corresponding RPE levels with a high percentage (+80 % for most levels).

Taken together, we found partial support for our hypotheses. Overall, the force output increased with each RPE level. When feedback was available, people produced different force outputs for all prescribed levels of the scale. This was also found to be the case when no concurrent visual feedback was available, and people had to rely solely on their feelings of effort. The resulting slope indicates that the internal model of mapping RPE onto performance is only fully linear when feedback is available. As expected, an effect of social facilitation on force output was found in the form of increased overall force output.

4.1. Theoretical and practical implications

Our study revealed that the way people transpose prescribed RPE levels into force is a dynamic process, in the sense that the mapping varies as a function of situational psychological factors. Our findings have important implications for the understanding of the RPE-performance mapping in prescription contexts. Below, we will discuss three tentative interpretations of our findings in more detail.

First, our research focused on the question of how much force a person produces at a prescribed RPE level. In this context, higher performance must not be equated to better performance. This is in contrast to most settings, where higher performance equates to a better result. In these latter conditions, a large body of research has shown that providing feedback or the presence of others improves performance and increases invested effort (Baker et al., 2011; Ekblom & Eriksson, 2012; Fischer et al., 2010; Marcel-Millet et al., 2021; Sheridan et al., 2019). However, it has recently been highlighted that under such conditions, performance, feedback, and the exertion of effort might actually be confounded, as higher effort could be equivalent to better performance (Xu et al., 2023). In an attempt to de-confound this, Xu et al. (2023) had participants squeeze a handgrip dynamometer within a target range and provided them with non-veridical feedback regarding their performance. Interestingly, participants squeezed the dynamometer progressively harder if they received negative feedback, although producing higher forces did not equate to better performance and the feedback was unrelated to their actual performance. This is somewhat consistent with our findings, where in the feedback condition, participants adjusted their behavior without necessarily improving their performance. Thus, while our findings seem to add to the large body of research on the performance-enhancing effects of feedback and social facilitation, they reveal some interesting insights into how these factors might affect the effort-performance relationship: concurrent feedback and the presence of others seem to enhance performance (i.e., people squeeze harder) but might not necessarily make it better if effort and performance are de-confounded.

Second, why did participants produce more (and linearized) force when they had access to visual feedback? Based on past research, one explanation for this finding is that concurrent visual feedback introduced higher levels of motivation and competitiveness in the participants (Weakley et al., 2019; Wilson et al., 2017). This change in emotions consequently led to participants interpreting their effort feelings differently, which was expressed as squeezing harder. While it is well established that one's emotional state and strength are linked (Jiang et al., 2022), this would not necessarily explain the linearization of force. We would argue that this result can be explained by a strategic component. It is possible that when participants saw their produced forces on the screen, they assumed that they should exert force in a way where RPE 4 equals half of RPE 8, RPE 2 equals half of RPE 4, and so on, which would result in a linear output and steady increases between the levels. The more "pure" measurements without feedback, where this calculation could not be performed and people had to rely solely on their RPE, indeed revealed additional quadratic and cubic trends, which subsequently led to lower average force production.

A further speculative interpretation for the convex relationship between RPE and force in the no feedback condition might be added mental effort demands to produce force that accurately reflects one's RPE. Consistent with this, participants found producing moderate RPE levels to be the most challenging, and they produced relatively lower forces at these RPE levels. This tentative interpretation is consistent with recent work, arguing that effort costs are integrated across domains and that the specific costs vary as a function of the required effort level (Rewitz et al., 2023).

Third, in terms of social facilitation, our data indicates that the presence of another person led to an increase in average force output, which is in line with past studies (Baker et al., 2011; Sheridan et al., 2019). A proposed explanation for the increase in force is based on higher ratings of self-efficacy that are exhibited in the presence of another person (Sheridan et al., 2019). With respect to the associations between RPE and social facilitation, past research demonstrates inconclusive results. For instance, Sheridan et al. (2019) found reduced RPE in the presence of another person, while Leitzelar et al. (2016) and Carnes et al. (2013) found no differences in RPE ratings in combination with social facilitation. At this point, no uniform conclusions on the influence of social facilitation on RPE can be drawn.

Part of the reason it is difficult to describe the process of transforming ratings of effort into force output is the multitude of factors that might impact this relationship. Among them are the frequency of repetitions, the number of values used from the RPE scale, the validity and reliability of outcome measures (single vs. multi-joint; isometric vs. dynamic contractions), the definition of perception of effort, and the clarity of the rating instructions. To illustrate, RPE has been shown to differ between concentric and eccentric contractions (Hollander et al., 2003) and is influenced by the total time of a muscle contraction (Diniz et al., 2014). Adding to this, Malleron et al. (2023) have recently pointed out that the way the upper limit of an RPE scale is anchored (i.e., self-selected vs. imposed) greatly influences RPE during strength tasks. Further, researchers often use different scales for RPE measurements, which may also impact the shape of these relationships (Halperin & Emanuel, 2020). In summary, there appear to be various variables that influence the relationship between RPE and force production, and more research is needed to clarify the impact of these variables.

From an applied perspective, our findings provide interesting insight insofar as subjects produced different levels of force across the ten RPE levels. In the past, Morrin et al. (2018) have demonstrated that using singular levels of RPE as a prescription tool can be successfully implemented in people with high blood pressure. In our case, a trainer's instruction could be: "For the next contraction, I want you to exert a level of force that feels like a seven out of ten to you." In this example, trainees should be able to produce force that is distinguishably lower than a rating of eight and higher than a rating of six. However, the application of our findings is limited and should be met with caution. We found that the RPE levels did not consistently correspond to MVC levels, meaning that an RPE of 7 did not reliably align with 70 % of MVC. This is in line with past research, where both overproduction and underproduction of force in RPE prescription tasks have been observed (Jackson & Dishman, 2000; Pincivero, 2011; Pincivero et al., 2003a). In order to precisely prescribe exercise intensity, using classical methods for load prescription (e.g., working with repetitions that are based on %MVC or %1RM) might be preferable, as the used weight or load can be determined beforehand. However, employing RPE for prescription can still be useful, as 1RM testing includes additional factors such as the need for supervision or prior knowledge of the movement, and not all populations (e.g., elderly people) are able to perform 1RM testing.

In line with past research, our data demonstrates that the mere presence of a person can have a positive effect on force output (Edwards et al., 2018; Sheridan et al., 2019). In a practical setting, this knowledge could be applied by training in a social environment and using training partners as spotters. However, as mentioned previously, in the context of our study, higher force was not truly indicative of better performance but rather indicated that the mapping of how hard one should squeeze at a given RPE had been changed. Thus, while social facilitation may improve performance, one should also be cautious that, by altering the RPE-performance relationship, it might prompt an athlete to train harder than they intended.

Lastly, our study indicates that providing visual feedback on effort-based force production can lead to an increase in force output. Research in the past has demonstrated that concurrent feedback can lead to performance increases in strength-based tasks (Ekblom & Eriksson, 2012; Fischer et al., 2010; Marcel-Millet et al., 2021). However, the practical application of this finding is rather limited, as we are not aware of feedback-based devices in the health or fitness industry that currently use RPE-based load prescription for resistance training.

4.2. Limitations and future directions

Given that our sample predominantly consisted of young adults, the generalizability of our findings is limited. As past research has demonstrated, there are notable differences between young and elderly individuals regarding their force output and their perception of effort (John et al., 2009; Pincivero, 2011). It might further be argued that the majority of study participants in our sample were male, and differences in strength between sexes are well established (Bartolomei et al., 2021; Leyk et al., 2007). However, in their meta-analysis, Lea et al. (2022) suggest that, concerning RPE ratings, sex differences might be negligible.

By looking at average values in our analysis, one could contend that our findings may have limited applicability when it comes to individual cases. However, as shown above (Figure 3), subjects were generally able to successfully differentiate their force output for each RPE level.

Finally, we observed that the employed protocol, consisting of 20 contractions (one per RPE value, repeated two times), led to some muscular fatigue, as evident by an average reduction of ~15 % in MVC values in the post-protocol test. Muscular fatigue is known to alter one's sense of limb position (Proske, 2019) and reaction time (Soto-Leon et al., 2020). Therefore, it is possible that the induced fatigue observed in our study may have modified the strength and shape of the associations between the prescribed RPE values and the corresponding forces. To better understand the impact of fatigue on these associations, future research could employ protocols leading to less fatigue, possibly by increasing rest intervals between contractions.

5. Conclusion

Here, we showed that the process by which individuals transpose force prescribed by RPE levels into objective output is contingent upon various factors. The availability of feedback and the presence of another person performing the same task not only influenced the total force output but also the slope of the produced force and even the MVC. These findings provide valuable information from both a theoretical and practical standpoint and shed light on the intricate mapping between RPE and performance.

Ethics

The present study falls outside the range of research requiring ethics approval according to the position of the local ethics committee (university name removed). All subjects gave written informed consent in accordance with the Declaration of Helsinki.

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CRediT authorship contribution statement

Felix Weilharter: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Katja Rewitz:** Writing – review & editing, Data curation, Formal analysis, Software, Visualization. **Israel Halperin:** Supervision, Writing – review & editing. **Wanja Wolff:** Conceptualization, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data is available online: https://osf.io/3ps4a

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