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ORIGINAL ARTICLE

More bang for the buck: autonomy support increases muscular efficiency

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Abstract

The purpose of this study was to examine whether conditions that provide performers with a sense of autonomy, by giving them choices, would increase movement efficiency. We evaluated neuromuscular activation as a function of choice, using surface electromyography (EMG), during isometric force production. Participants ($N=16$) were asked to perform plantar flexions at each of three target torques (80%, 50%, 20% of maximum voluntary contractions) under both choice and control conditions. In the choice condition, they were able to choose the order of target torques, whereas the order was pre-determined in the control condition. Results demonstrated that while similar torques were produced under both conditions, EMG activity was lower in the choice relative to the control condition. Thus, providing performers with a choice led to reduced neuromuscular activity, or an increase in movement efficiency. This finding is in line with the notion that autonomy support readies the motor system for task execution by contributing to the coupling of goals and actions (Wulf and Lewthwaite, Psychon Bull Rev 23:1382–1414, 2016).

Introduction

Conditions that grant individuals a certain degree of autonomy have been demonstrated to be important for optimal motor performance and learning (for a recent review, see Wulf & Lewthwaite, 2016). Numerous studies related to learner-controlled practice have provided evidence that learning is enhanced by giving performers control over the timing and frequency of feedback (e.g., Aiken, Fairbrother, & Post, 2012; Chiviacowsky & Wulf, 2002; Janelle, Barba, Frehlich, Tennant, & Cauraugh, 1997), demonstrations of the skill (e.g., Ste-Marie, Vertes, Law, & Rymal, 2013; Wulf, Raupach, & Pfeiffer, 2005), use of assistive devices (Chiviacowsky, Wulf, Lewthwaite, & Campos, 2012; Hartman, 2007; Wulf & Toole, 1999), amount of practice (e.g., Lessa & Chiviacowsky, 2015; Post, Fairbrother, & Barros, 2011), or other variables. Even if the choices learners make are more or less incidental to the task—such as the color of balls to be used (Lewthwaite, Chiviacowsky, Drews, & Wulf, 2015, Experiment 1), the color of a mat to be placed under a target (Wulf, Iwatsuki, Machin, Kellogg, Copeland, & Lewthwaite, 2018), or the order in which to perform certain tasks (Wulf & Adams, 2014)—learning has been found to be more effective compared with no-choice conditions. In one study that directly compared the effectiveness of task-relevant versus task-irrelevant choices, both types of choices equally benefited motor learning (Wulf et al., 2018, Experiment 2). Interestingly, in a meta-analysis (Patall, Cooper, & Robinson, 2008), instructionally irrelevant choices were found to be more motivating compared with relevant ones.

In addition to the longer-term benefits for motor skill learning, having choices has been found to have immediate positive impacts on motor performance. For example, when kickboxers were able to choose the order of different punches, the velocity and forces of those punches were greater relative to a condition in which punches were performed in a prescribed order (Halperin, Chapman, Martin, Lewthwaite, & Wulf, 2017). In another study (Iwatsuki, Abdollahipour, Psotta, Lewthwaite, & Wulf, 2017), repeated maximal effort trials involving a hand dynamometer resulted in sustained maximum forces when participants were able to choose the order of their right and left hands. In contrast, forces declined in a yoked control group. Finally, allowing performers to select pictures to be viewed during a

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submaximal run (65% of VO_2max) on a treadmill increased running efficiency, as measured by oxygen consumption and heart rate, compared with performers' viewing the same picture but without having a choice (Iwatsuki, Navalta, & Wulf, 2019).

Thus, giving individuals a sense of autonomy through the provision of choices has consistently been demonstrated to result in learning and performance advantages. Autonomy support is therefore one of three key variables in the OPTIMAL theory of motor learning (Wulf & Lewthwaite, 2016). (The other key variables are enhanced expectancies and an external focus of attention.) According to the theory, autonomy-supportive conditions are rewarding (Murayama, Izuma, Aoki, & Matsuyama, 2016) and thus increase individuals' anticipation or expectations for future reward or success (Hooyman, Wulf, & Lewthwaite, 2014; Lemos, Wulf, Lewthwaite, & Chiviacowsky, 2017; Murayama et al., 2016). Expectations for positive experience, in turn, elicit dopaminergic responses that facilitate the establishment of functional neural connections necessary for successful motor performance, including the production of force (Foreman, Singer, Addison, Marcus, LaStayo, & Dibble, 2014). In addition, autonomy support allows performers to focus their attention (externally) on the task goal, without the need for self-regulatory activity resulting from controlling environments (e.g., Reeve & Tseng, 2011). In the OPTIMAL theory (Wulf & Lewthwaite, 2016), performer autonomy is considered an important contributor to goal–action coupling, that is, the linking of movement goals with necessary (cognitive, neural, and neuromuscular) actions. It is a precondition for effective and efficient motor performance, or the fluidity with which the intended movement goal is translated into action. The benefits of choices for movement effectiveness, such as accuracy (e.g., Wulf et al., 2018), timing (e.g., Chiviacowsky & Wulf, 2002), balance (e.g., Wulf & Toole, 1999), or movement form (e.g., Aiken et al., 2012; Lemos et al., 2017; Ste-Marie et al., 2013), and movement efficiency, such as reduced oxygen consumption (Iwatsuki et al., 2019) or sustained maximum force production (Iwatsuki et al., 2017), are consistent with the notion of goal–action coupling being promoted by autonomy-supportive conditions.

However, evidence for increased movement efficiency resulting from autonomy support is limited and indirect (Halperin et al., 2017; Iwatsuki et al., 2017, 2019). We therefore deemed it important to use a more direct measure of neuromuscular efficiency. We examined effects of performer autonomy on motor performance by measuring neuromuscular activity through the use of electromyography (EMG). Participants were asked to perform a motor task that involved the production of accurate forces through ankle plantar flexion (see also Lohse & Sherwood, 2012; Lohse, Sherwood, & Healy, 2011). All participants performed three variations of the task (i.e., different target torques) under both choice and control conditions. We hypothesized that allowing participants to choose the order of task variations would result in increased efficiency, as reflected by reduced EMG activity, relative to the no-choice control condition.

Method

Participants

Participants were 16 college students (11 females, 5 males) with an average age of 22.75 years (SD = 2.35). Their average weight was 70.67 ± 12.62 kg, and average height was 168.86 ± 7.09 cm. The study was approved by the university's institutional review board. Prior to the experiment, all participants gave written informed consent. Participants were not aware of the specific purpose of the study.

Apparatus and task

A HUMAC NORM Isokinetic Extremity System Dynamometer (Computer Sports Medicine Inc., Stoughton, Massachusetts, USA) was used to record torques generated through plantar flexion of the dominant leg. A seat belt, double shoulder belts, and a thigh stabilization belt were used to prevent muscle substitutions (see Fig. 1). We chose isometric contractions as they involve only minimal changes of muscle fiber length (theoretically no changes), thereby limiting muscle fiber orientation. Changes of muscle fiber orientation can influence the number of muscle fibers and motor units underneath the electrode, which in turn can affect the recording (Cresswell, Löscher, & Thorstensson, 1995). Furthermore, under isometric contraction, the linearity of EMG and torque is retained, while this is not the case under isotonic contraction (Weir, Wagner, & Housh, 1992). Thus, to be sure that any non-linear EMG manifestation was due to our experimental manipulation, and not to movement-related artifacts, we used an isometric test. Muscle activation during isometric contractions of the medial gastrocnemius

Fig. 1 Experimental setup

was obtained using surface EMG (Delsys Tringo wireless system, Natick, Massachusetts, USA). The medial gastrocnemius was selected because it shows a more stable linear relationship between EMG activity and different contraction levels than does the soleus (Cresswell et al., 1995). The EMG signal was recorded with the Nexus Motion Capture Software (Oxford Metrics, Oxfordshire, UK) at a sampling frequency of 2000 Hz.

Procedure

Participants were seated in the dynamometer according to manufacturer guidelines. Their task was to perform isometric plantar flexions with the dominant leg. To determine leg dominance, participants were asked which leg they used to kick a soccer ball. They were instructed to push the top of the force platform away with the front part of their shoe. They practiced with submaximal effort until they felt comfortable with the dynamometer.

Before data collection began, the skin was prepared by shaving and cleaning it with alcohol to reduce skin impedance. An electrode was positioned to record the activity of the medial gastrocnemius. The parallel bars of the electrode were placed in the direction of the muscle fibers. An elastic bandage was wrapped around the electrode to secure it from extraneous movement without hindering movement about the knee joint. All plantar flexor isometric contractions were performed within one testing session, and no electrode replacement was necessary during the experiment.

There were three target torques corresponding to 80%, 50%, and 20% of the participant's maximum voluntary contraction (MVC). To determine MVC, participants were instructed to produce maximum torque as quickly as possible and hold it for 4 s. They performed three trials with 1-min rest periods between trials. The highest torque produced over the last 3 s of those trials was used as the participant's MVC. Subsequently, each participant performed three trials (after one practice trial) under each of the three target torques (80%, 50%, and 20% of MVC), with 30-s rest periods between trials. On a computer monitor, a line representing the target torque as well as the remaining time was displayed. Participants were asked to reach the target line as quickly as possible and to maintain that force level for 10 s.

In the choice condition, participants were asked to choose which target torque (80%, 50%, or 20%) they wanted to use on their first three trials. After completing those trials, they were asked to choose the second target torque. Finally, they performed the last three trials with the remaining target torque. In the control condition, participants were assigned the order of target torques. That order was determined by the previous participant's selections in the choice condition. (The very first participant was given an order determined by the experimenter: 80%, 50%, 20%.) Half of the participants performed the choice condition first, while the other half performed the control condition first. The rest period between the choice and control conditions was 10 min.

Dependent variables and data analysis

For each 10-s trial, the torque produced by a participant was averaged for seconds 3–9 (i.e., across 7 s), where torques were relatively steady. Similarly, we used seconds 3–9 for analysis of the EMG data. The raw EMG signal was converted to root mean square error (RMSE). A total of 14000 samples (7 s × 2000 samples per second) was used. EMG data were normalized to the maximum value obtained during the participant's MVC. A customized MATLAB (MathWorks Inc., Natick, MA, USA) program was utilized to extract raw EMG data.

Assumptions of normality for both torque and normalized EMG data (i.e., EMG RMSE) were tested using the Shapiro–Wilk test ($\alpha = 0.05$). Torque data were normally distributed. However, the assumption of normal distribution was violated for the normalized EMG data. Therefore, the normalized EMG data were log transformed [log10 $(x_i + 1)$] (Field, 2009, p. 151; see also Csibra, Hernik, Mascaro, Tatone, & Lengyel, 2016). The log-transformed normalized EMG was normally distributed and therefore used for analysis. Torque and log-transformed EMG data were analyzed in 2 (condition: choice vs. control) × 3 (target torque: 80%, 50%, 20% of MVC) × 3 (trials) analyses of variance (ANOVAs) with the repeated measures on all factors. Mauchly's test was utilized to assess the sphericity assumption. If the assumption was violated, the Greenhouse–Geisser epsilon values were used to adjust the degrees of freedom. Bonferroni corrections were performed for all adjustments and post hoc tests. Estimates of effect size were quantified using two measures. First, the partial eta squared measure (η_p^2) was employed, where $\eta_p^2 = 0.01$, 0.06, and 0.14 were estimated for a small, moderate, or large effect, respectively (Cohen, 2013; Lakens, 2013). Next, Cohen's *d* was utilized as a measure of difference between group means using the repeated-measures version of Cohen's *d* that factors in the correlation between time points (Morris & DeShon, 2002). The evaluation of Cohen's *d* corresponded to low ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$) effects (Cohen, 2013; Lakens, 2013). The level of significance was set to 0.05. All analyses were performed using the Statistical Package for the Social Sciences (IBM Statistics 24.0; SPSS Inc., Chicago, IL).

Results

Maximum voluntary contractions and order of target torques

Average MVCs resulted in 75.4 Nm (SD = 36.9). Thus, the average target torques used in this study corresponded to 60.3 Nm (80% of MVC), 37.7 Nm (50%), and 15.1 Nm (20%). Participants chose the 80% torque predominantly for the first block (75%) and to a lesser degree (25%) for the last block. The 50% torque was mostly chosen for the second block (87.5%), and 12.5% of the time for the third block. Finally, the 20% torque was performed first 25% and third 62.5% of the time.

Torque production

The average torques produced in the choice and control conditions at each level are shown in Fig. 2. As can be seen, torques were very similar in the two conditions. The main effect of condition was not significant, F (1, 15) = 2.429, $p = 0.140$, $\eta_\rho^2 = 0.139$. The main effect of target torque was significant, F (1.01, 15.17) = 70.36, $p < 0.000$, $\eta_\rho^2 = 0.824$. Post hoc tests indicated that torques produced at 80% ($M = 61.1 \pm 28.6$ Nm), 50% ($M = 38.9 \pm 18.2$ Nm), and 20% of MVC ($M = 16.5 \pm 7.8$ Nm) all differed from each other, ps < 0.001. There was no main effect of trial, F (2, 30) = 0.729, $p = 0.491$, $\eta_\rho^2 = 0.046$. The interactions of target torque and condition, F (1.43, 25.51) = 0.931, $p = 0.380$, $\eta_\rho^2 = 0.058$, target torque and trial, F (2.60, 38.99) = 1.478, $p = 0.028$, $\eta_\rho^2 = 0.090$, condition and trial, F (1, 30) = 1.203, $p = 0.314$, $\eta_\rho^2 = 0.074$, and target torque, condition, and trial were not significant, F (2.17, 32.48) = 1.928, $p = 0.159$, $\eta_\rho^2 = 0.114$.

EMG activity

Log-transformed normalized EMG activity at each target level for the choice versus control conditions, averaged across trials, can be seen in Fig. 3. EMG activity was generally lower in the choice condition. The main effect of condition was significant, F (1, 15) = 5.18, $p = 0.038$, $\eta_\rho^2 = 0.257$. Furthermore, EMG activity was highest at the torque corresponding to 80% of MVC and lowest at 20% (see Fig. 4). The effect of target torque was significant, with F (2, 30) = 222.12, $p < 0.001$, $\eta_\rho^2 = 0.937$. Post hoc tests indicated the differences between 80% and 50% ($p < 0.001$, $d = 2.338$), 80% and 20% ($p < 0.001$, $d = 4.204$), and 50% and 20% ($p < 0.001$, $d = 2.057$) were significant. The interaction of condition and target torque was not significant, F (2, 30) = 2.38, $p = 0.110$, $\eta_\rho^2 = 0.137$. EMG activity did not change across trials, and the main effect of trial was not significant, F (2, 30) = 0.56, $p = 0.5567$, $\eta_\rho^2 = 0.036$. Also, there were no significant interactions of condition and trial, F (2, 30) = 2.06, $p = 0.145$, $\eta_\rho^2 = 0.121$, torque and trial, F (2.19, 32.89) = 1.76, $p = 0.185$, $\eta_\rho^2 = 0.105$, or condition, torque, and trial, F (1.84, 27.69) = 1.59, $p = 0.221$, $\eta_\rho^2 = 0.096$.

Discussion

The present study followed up on recent studies that provided somewhat indirect support for the idea that the motor system operates at a higher level of efficiency when the performer has a sense of autonomy. In two of those studies, it was found that maximum force production was enhanced by performers having choices (Halperin et al., 2017; Iwatsuki et al., 2017), suggesting greater effectiveness and efficiency in motor unit recruitment. Those findings were the first to suggest that neuromuscular activity might be more effective under autonomy-supportive conditions. More direct

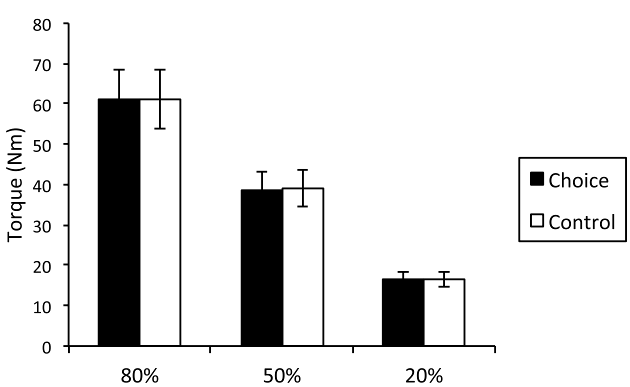

Fig. 2 Torques produced at each target level in the choice and control conditions

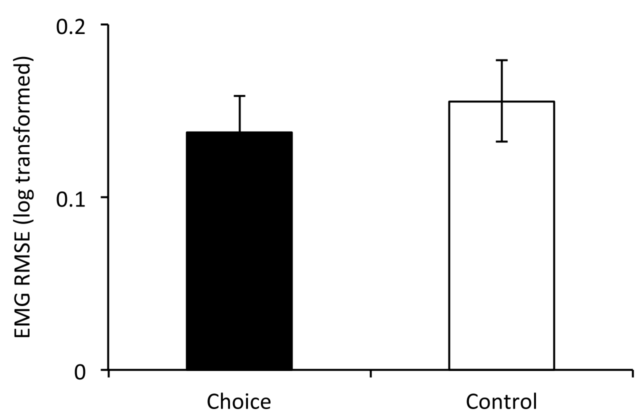

Fig. 3 Average of log-transformed normalized EMG activity in the choice and control conditions

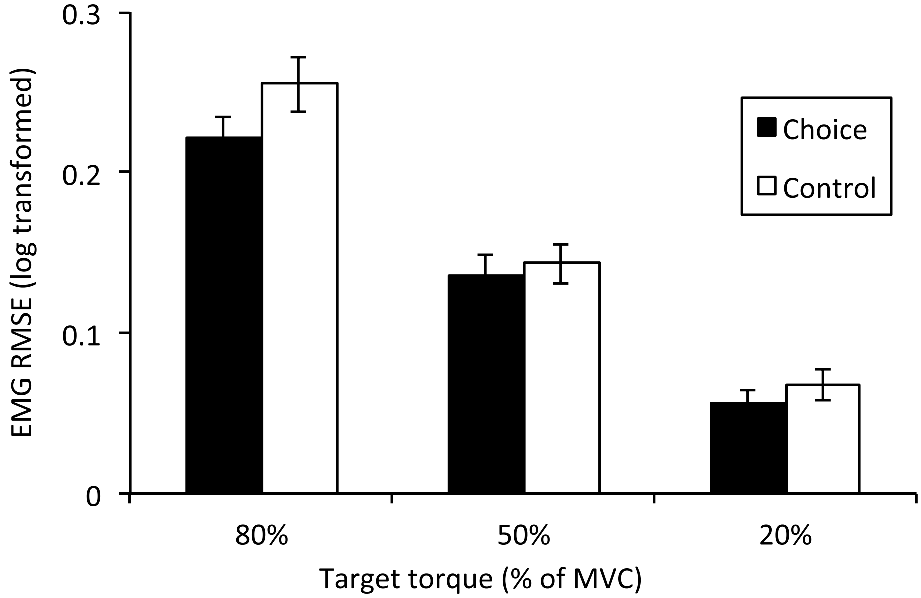

Fig. 4 Log-transformed normalized EMG activity at each target torque in the choice and control conditions

evidence for this idea was provided in a study by Iwatsuki et al. (2019), in which oxygen consumption during running was found to be reduced by the provision of choices. The present study was therefore designed to directly measure neuromuscular activity. The results were clear in showing that EMG activity was indeed lower in the choice relative to the control condition. This was the case even though the order of target torques was identical across choice and control conditions (with the exception of the first participant's torque order in the control condition), and participants produced very similar average torques in both conditions. Moreover, because one specific order of target torques (80%–50%–20%) was chosen the most, the chosen and assigned order happened to be the same for half of the participants (i.e., their yoked counterpart had chosen the same order). These findings highlight the importance of autonomy support as well as a neuromuscular pathway contributing to performance benefits associated with it (for a review, see Wulf & Lewthwaite, 2016). The present findings provide the first direct evidence that these benefits include the neuromuscular efficiency with which movements are performed.

Autonomy-supportive conditions have been shown to enhance expectancies for future performance, including self-efficacy (Hooyman et al., 2014; Lemos et al., 2017; Murayama et al., 2016; Wulf, Chiviacowsky, & Drews, 2015). Interestingly, when performance expectations were directly enhanced, for example, by providing positive performance feedback, movement efficiency also increased (e.g., Hutchinson, Sherman, Martinovic, & Tenenbaum, 2008; Montes, Wulf, & Navalta, 2018; Stoate, Wulf, & Lewthwaite, 2012). Furthermore, placebos, which target positive outcome expectations, have been found to enhance force production (Fiorio, Emadi Andani, Marotta, Classen, & Tinazzi, 2014; Kalasountas, Reed, & Fitzpatrick, 2007). Expectations of positive experiences are associated with the release of dopamine (de la Fuente-Fernández, 2009; Lidstone et al., 2010), which has directly or indirectly been shown to enhance movement efficiency and effectiveness (Foreman et al., 2014; Jenkinson & Brown, 2011; Meadows, Gable, Lohse, & Miller, 2016). Moreover, Lee and Reeve (2013) found that imagery of self-determined tasks, as opposed to tasks that were non-self-determined, was linked to the activation of the anterior insular cortex, a region of the brain associated with a sense of agency. This region is part of the brain's salience network and has been associated with task-switching functions (Menon, 2015) that might also contribute, via priming or task readying (Aarts, Custer, & Marien, 2008), to movement efficiency. Similar to self-determined situations, having choices induces a sense of agency, which is associated with dopamine release (Aarts, Bijleveld, Custers, Dogge, Deelder, Schutter, & van Haren, 2012). In future studies investigating the mechanisms by which autonomy support affects motor performance, researchers might consider dopaminergic/expectancy pathways as well as the priming functions of salience network activation.

Autonomy is assumed to help performers maintain a clear focus on the task goal while reducing a detrimental self-focus (e.g., McKay, Wulf, Lewthwaite, & Nordin, 2015; Pascua, Wulf, & Lewthwaite, 2015; see Wulf & Lewthwaite, 2016). Attention directed to the task goal (i.e., externally) has indeed been shown to not only enhance motor performance but also increase movement efficiency (i.e., reduce EMG activity) relative to a self-related or internal attentional focus (Lohse & Sherwood, 2012; Lohse, Sherwood, & Healy, 2010; Lohse et al., 2011; Marchant, Greig, & Scott, 2009; Vance, Wulf, Töllner, McNevin, & Mercer, 2004;

Wulf, Dufek, Lozano, & Pettigrew, 2010; Zachry, Wulf, Mercer, & Bezodis, 2005). A study by Chiviacowsky et al. (2012) demonstrated that a choice condition resulted in a reduced self-focus compared with a no-choice control condition. These findings corroborate the view that autonomy support may facilitate the establishment of neural connections needed for effective and efficient motor performance (e.g., Milton, Solodkin, Hluštík, & Small, 2007). At the muscular level, a task focus (or external focus) manifests itself in reduced co-contractions (e.g., Wulf et al., 2010; Zachry et al., 2005), more efficient recruitment of muscle fibers within muscles (Lohse et al., 2011; Vance et al., 2004), and optimized direction and timing of the contributing forces (Lohse, Jones, Healy, & Sherwood, 2014). It remains to be seen whether autonomy-supportive conditions have similar effects. Future studies will likely shed more light on this issue. In addition, it would be interesting to examine co-activation patterns of agonists and antagonists (e.g., Geertsen, Kjaer, Pedersen, Petersen, Perez, & Nielsen, 2013). Furthermore, it would be desirable to include different and more dynamic motor tasks in future experiments.

Aside from their theoretical importance, the present findings have implications for applied settings. They suggest that practitioners, such as coaches, trainers, or physical therapists, can help their athletes or clients move more effectively and efficiently by providing them with small choices or instructional language that is autonomy-supportive (Hooyman et al., 2014). Potential benefits include (competitive) performance advantages, experiences of movement fluidity and effortlessness, and longer practice durations.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Human and animal rights statement All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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