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Feasibility and early effects of bed-cycling eccentric training: potential clinical applications

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KEYWORDS

bedridden patients, exercise rehabilitation, muscle atrophy, negative work

Abstract

Purpose:

This study aimed to evaluate feasibility and early effects of moderate intensity bed-cycling eccentric training on healthy individuals, and establish whether this training modality could be **implemented into bedridden patients' routine care.**

Methods:

Longitudinal study with prepost exercise intervention measurements. The development of a bed-adapted eccentric ergometer allowed to conduct five training sessions during 3 weeks at increasing intensity on 11 healthy individuals. Force-speed relationship, maximal voluntary knee extension force and neural activation of subjects were evaluated before and after the programme.

Results:

Five training sessions were sufficient to decrease the rate of perceived exertion whereas eccentric power output increased (+40%). After training, maximal voluntary isometric contraction force measured during knee extension had significantly improved in all subjects, with a mean increase of 17%. Maximal cycling power was also significantly higher (+7%) after the training programme.

Conclusion:

Taken together, these results show that moderate load eccentric bed cycling (i) was feasible and efficient, (ii) did not generate excessive individual perception of effort during exercise nor develop major muscular or joint pain after training and (iii) allowed early force and power gains in healthy subjects.

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INTRODUCTION

In sedentary patients, exercise has numerous beneficial effects, maintaining lower limbs function and functional independency (Brown et al., 1995; Johansen, 2008; Painter et al., 2000; Westhoff et al., 2000). Cycling is the most common practice but concentric contractions linked to this activity generate high metabolic demand and extreme caution should be taken in frail patients like those suffering of end-stage renal disease (ESRD), cardio-vascular pathologies or severe sarcopenia. Consequently, eccentric cycling, where pedals are driven by an engine and subjects have to brake their rotation, could be an attainable, efficient and complementary

rehabilitation method. This modality permits to achieve high work-loads at low metabolic cost (Hoppeler, 2016). Energy required for muscle lengthening is four to six-fold lower than for shortening (Abbott et al., 1952; Bigland-Ritchie & Woods,1976; Perrey et al.,2001) thanks to mini-cycles of myosin binding without adenosine triphosphate (ATP) consumption (Vale & Milligan,2000) and to the wrapping of titin around actin although the exact role of titin in force generation and transmission is subject to debate (Oranchuk et al., 2019). Series and parallel elastic components including tendon and other connective tissues like endo, peri and epimysium are also decisive for the eccentric strength production (Magnusson & Kjaer,2019; Oranchuk et al.,2019).

Recent works reported the feasibility of moderate load eccentric bed cycling during dialysis and the use of eccentric-overload resistance exercise as a potential treatment to combat decline in physical function in people with chronic kidney disease (CKD; Pavlin et al.,2022). (Gollie et al., 2020).Eccentricexercisewasshowntobefeasibleforpatientswithcardiorespiratory limitations (Besson et al.,2013; P. La Stayo et al.,2014).In the elderly, higher improvements in physical function were evidenced following an eccentric training compared to a concentric mode. This study showed that physical fitness and maximal concentric contraction strength of the knee extensors increased more after progressive eccentric training than after progressive concentric training (Chen et al.,2017). In the same population, improvements of strength and physical function were similar after an eccentric and a high-velocity training, whereas total work was lower in the eccentric training programme (Leszczak et al., 2013). In a systematic review, Douglas concluded that eccentric resistance training may be more particularly beneficial than concentric resistance training to improve strength, power and speed performance (Douglas et al.,2017).However, eccentric modality is underused in rehabilitation, because contractions are often associated with micro-damages in fibres structure causing Delayed Onset Muscle Soreness (DOMS; Proske & Morgan,2001; Vogt & Hoppeler,2014). It is noteworthy that muscle fibres can be preserved, as progressive workload increase confers an early protective effect to muscles and tendons (Chen et al., 2017; Lin et al.,2015;McHugh,2003). When intensity was based on rate of perceived exertion(RPE), no pain has been reported (Besson et al., 2013; P. La Stayo et al.,2014). Fractioned practice seems to promote this 'repeated bouteffect'(RBE), allowing naive subjects to perform eccentric contractions without DOMS(Steineretal.,2004; Vogt & Hoppeler,2014). Feasibility and efficiency of eccentric training were evidenced in chronically ill patients but were not explored in a lying position (Hoppeler,2016;P.C.LaStayo et al.,2010; P. La Stayo et al.,2014; Steiner et al.,2004).Compared to eccentric exercise performed in the standing, sitting or semi-recumbent postures, the supine position has several special characteristics. Since the strength produced by the vastus lateralis, which is part of the Quadriceps muscle, depends on the knee and hip flexion angle, body position is a crucial parameter for cycle training efficiency (Bordoni & Varacallo, 2022). During supine exercise where the active musculature is a tor above the level of the heart, the gravitational assistance to muscle blood flow is absent and muscle perfusion pressure is reduced resulting in slowed tissues oxygenation (Goulding et al.,2020;Jones et al.,2006; Macdonald et al.,1998). This posture dependent alteration in active muscles perfusion could explain why performance on cycle ergometer is improved in the standing position (Astrand & Saltin,1961). Moreover, during concentric recumbent cycling, it was highlighted that pedalling effort was more equally distributed between the front and rear thigh muscle groups compared to standard upright position. It was also evidenced that cardiovascular response differs between positions, recumbent cycling being associated with lowers heart rate and systolic blood pressure, resulting in lower perceived exertion. This

difference is probably due to the horizontal leg position, facilitating blood return to the heart and reducing physiological stress (Wehrle et al., 2021). Given that ESRD disease patients often suffer from high blood pressure and cardiac issues, supine position seems to be associated with lower physiological stress and cardiovascular effort at the same work level than up right position. These results obtained for concentric cycling show that physiological and psychological responses to recumbent eccentric cycling may differ from those to upright or semi-recumbent positions. In ESRD patients, dialysis procedure progressively removes fluid overload accumulated in different cellular compartments, including general blood circulation. This decrease in circulating volume declines blood pressure as well as cardiac input and organ perfusion (Flythe et al., 2020), making supine position the only safe enough for those highly deconditioned patients. By decreasing gravitational vertical force, supine position facilitates venous blood return and diminishes hypotension risk and its consequences on heart function during fluid removal. Thus, a better understanding of eccentric cycling in this lying position is needed for exercise practice during dialysis procedure. Furthermore, despite the benefits of eccentric cycle training, the great heterogeneity of existing protocols and the variety of physiological responses in relation to the solicited muscle groups make it difficult to propose the best training procedures that optimally combine management of DOMS and muscular beneficial effects in terms of strength, power and coordination. (Douglaset al., 017; Vogt & Hoppeler, 2014).

Facing an important need for bed practice exercise facilities, we designed a study protocol to explore the feasibility and the early efficiency of bed-cycling eccentric training, highlighting the early effects of eccentric cycling on healthy volunteers trained in a lying position similar to that adopted by bedridden patients. Progressive increment of workload and exercise duration was planned to practice eccentric cycling safely without DOMS. Power, force and speed outputs, RPE, DOMS and heart rate frequency were monitored during all sessions whereas parameters of power-speed relationship, maximal voluntary contraction force and neural activation during maximal contraction were evaluated before and after training.

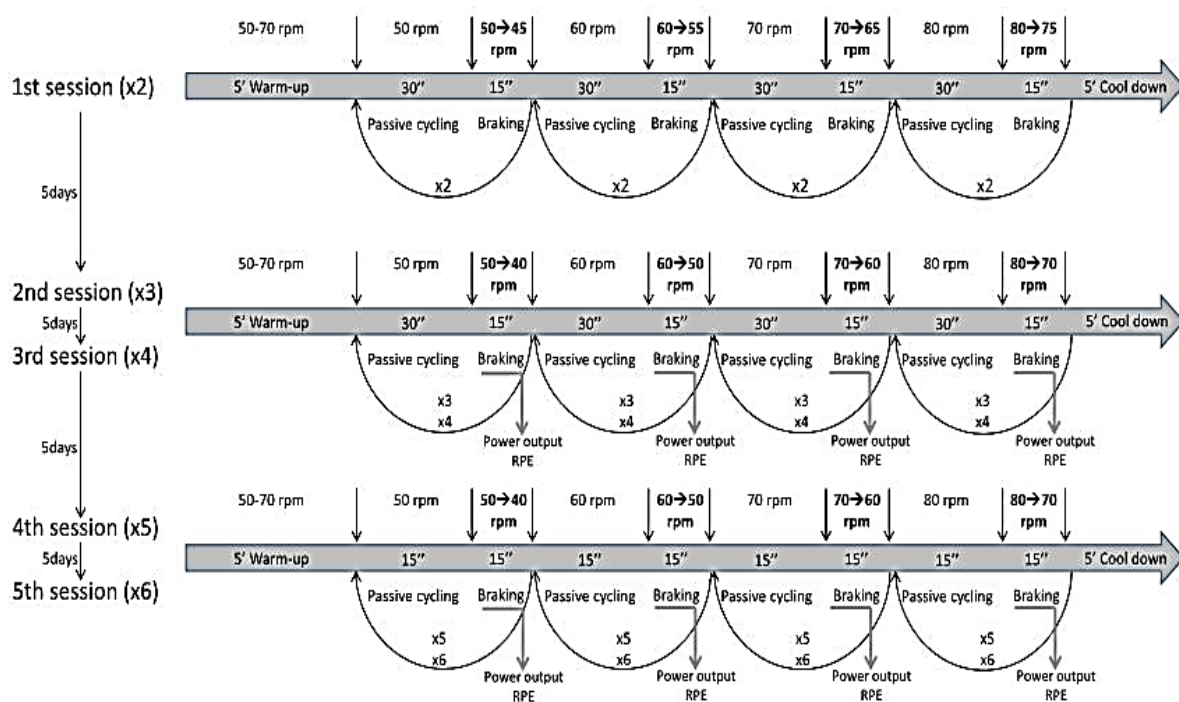


FIGURE 1 Experimental protocol of the study.

2|METHODS

2.1|Participants, study protocol and design

The study procedures complied with the Declaration of Helsinki and its later amendments on human experimentation and were approved by the national ethics committee. 11 healthy volunteers, including 6 males, were recruited and gave written informed consent. They were normal active people without medical contraindication to practice physical activity and he was asked to participants to keep their physical activity, their dietary and sleep habits during the 3-week training. Participants were evaluated before and after the five training sessions at increasing intensity during a 3 weeks period. Sample size for before-after study was estimated by G*Power (G*Power 3.1.9.7, Heinrich-Heine Universität Düsseldorf, Düsseldorf, Germany) in an a priori way by using repeated measures ANOVA

Considering a type I error rate of 0.05, a type II error rate of 0.2 (Cohen, 1988), an effect size of 0.5 (medium size effect, [Čretnik et al., 2022; Roig et al., 2009]), the calculated sample size was 10. We took a small margin of 10% to ensure this number of 10 measurements and involved 11 participants.

2.2|Home-made eccentric ergometer

The construction of an ergometer was necessary due to the lack of commercially available eccentric ergometers. Inspired by a guide previously published (Elmer & Martin, 2013), the ergometer was designed with a direct-drive motor for electric bikes fixed on a patient lift. The chain was linked to a SRM crankset equipped with bike pedals. To follow the requested target speed, the participants had a live speed display in front of them. Eccentric workload was measured by using bicycle SRM power meter (Elmer & Martin, 2013; Harrison et al., 2020; Leong et al., 2014; Lewis, 2012; Lewis et al., 2018).

2.3|Training procedure

Before exercise, subjects were equipped with a heart rate transmitter belt and cycling shoes. They were installed on the eccentric ergometer and asked to avoid arm or trunk movements. During each session participants were asked to perform passive anti-clock wise cycling (i.e., without braking phase) and to keep the speed rotation between 50 and 70 rpm during the five-min warm-up. The intensity of the effort as well as the workload were not fixed in advance and the same task of braking to reach the target speed as quickly as possible was asked to each participant. During the first session, considered as a familiarization session, ergometer speed was successively set at 50, 60, 70 and 80 rpm and subjects were asked to brake the pedals movement until the speed decreased by 5 rpm during 15 s, before 30 s of cool-down in passive cycling. First acclimatization session permitted for everyone to adjust the force applied to the pedals to achieve the goals previously explained and with the help of the advisor supervising the training. The RPE value given by the participants was used as feedback to better understand their feeling about bed-eccentric cycling at different speeds. Exercise was repeated twice for each speed. During the second session, ergometer speed was successively set at 50, 60, 70 and 80 rpm and subjects were asked to brake the pedals

movement until the speed decreases by 10 rpm during 15 s, before 30 s of cool-down in passive cycling. Exercise was repeated three times for each speed. The third session ergometer speed was successively set at 50, 60, 70 and 80 rpm and subjects were asked to brake the pedals movement until the speed decreases by 10 rpm during 15 s, before 30 s of cool-down in passive cycling. Exercise was repeated four times for each speed. The fourth session ergometer speed was successively set at 50, 60, 70 and 80 rpm and subjects were asked to brake the pedals movement until the speed decreases by 10 rpm during 15 s, before 15 s of cool-down in passive cycling. Exercise was repeated five times for each speed. The fifth and last session ergometer speed was successively set at 50, 60, 70 and 80 rpm and subjects were asked to brake the pedals movement until the speed decreases by 10 rpm during 15 s, before 15 s of cool-down in passive cycling. Exercise was repeated 6 times for each speed. At the end of each session participants were allowed to cool down in passive cycling for 5 min (Figure 1). In this training procedure, we considered that resistive force to decrease the speed by 10 rpm was steady whatever the rotating speed. Since the power output is the product of resistive force and velocity, power output increases with pedalling velocity.

2.4|Eccentric power and speed outputs

Power developed to brake and rotation speed of the pedals were monitored with a SRM 6 power control device (Schoberer Rad Meß technik GmbH; Gardner et al., 2004).

2.5|RPE in training procedure

The RPE was requested for each exercise of each session (Figure 1). Participants were asked to quote their effort using a revised Borg scale (0 to 10 scale [Williams, 2017]) and confirmed the value with an adjective: zero effort, extremely easy...very hard and extremely hard. The RPE scale was explained as follow: 'Given that 0 corresponds to any effort, like lying on a bed, and 10 to the most strenuous exercise close to exhaustion, how would you rate this exercise?'. Rating combined all the sensations and feelings of physical stress.

2.6|Delayed onset muscle soreness

A general rating of muscle soreness was assessed using a 10-point scale. A score of 0 corresponded to a rating of no pain, while a score of 9 corresponded to a rating of unbearable pain (McCormack et al., 1988). Subjects were requested to rate discomfort in quadriceps and calf regions of the legs, particular attention was paid concerning joint pains. Patients were asked to report any pain in the hip, knee and ankle joints. Soreness measures were collected 48 h following the session.

2.7|Concentric power-speed relationship

Before and immediately after the end of the training programme, subjects performed sprints on an instrumented ergometer (Monark 818E, Monark Exercise AB). After 5 min of warm-up, five consecutive sprints were recorded during 4 s with a sampling frequency of 200 Hz. Increasing loads were set successively at 0.2, 0.4, 0.6, 0.8 and 1 N.kg⁻¹. Maximal power output was extracted from the power-speed relationship with a third-order polynomial regression according to the method previously published (Arsac et al., 1996).

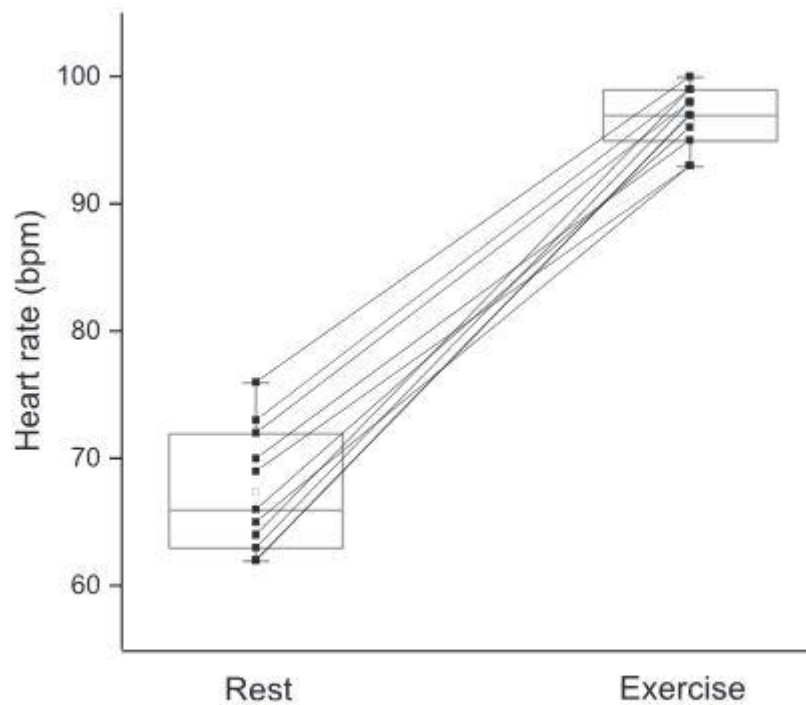


FIGURE 2 Heart rate frequency group data during rest and exercise.

TABLE 1 Characteristics of subjects at the beginning of the study

Subject	Gender	Age (years)	Height (m)	Weight (kg)	BMI
1	Male	53	1.72	77	26.0
2	Male	24	1.74	70	23.1
3	Male	53	1.72	67	22.6
4	Male	32	1.76	85	27.4
5	Male	24	1.85	82	24.0
6	Male	51	1.76	73	23.6
7	Female	24	1.77	70	22.3
8	Female	51	1.57	48	19.5
9	Female	55	1.74	67	22.1
10	Female	31	1.60	53	20.7
11	Female	44	1.65	58	21.3
Mean ± SEM		40.2 ± 4.0	1.72 ± 0.02	68.2 ± 3.5	23.0 ± 0.7

Abbreviation: SEM, standard error of the mean.

2.8|Maximal voluntary isometric contraction force

Before and immediately after the end of the training programme, maximal voluntary isometric contraction force (MVC) was measured during knee extension with a handheld dynamometer (Microfet2, Hoggan Health). Dynamometer was fixed behind the subject and an inelastic strap was used to link the leg, according to the method previously published (Souweine et al.,

2017). MVC of quadriceps of dominant leg was measured seated, hanging legs, without dorsal support with the knee held at 90° from extension, and arms crossed in front of chest. Before measurements, subjects were allowed to perform two trial contractions. After 1 min rest, subjects performed three maximal contractions of 4 s separated by 1 min rest. The maximal value was retained as MVC (100%). During MVC measurement, participants are seated with the hip angle near 90°. Supervisor ensured that the subjects are sitting naturally with a hip angle close to 90°, without any particular constraint, and does not make any upper body movement that could alter their postures (Garnieret al., 2022).

2.9|Neural activation during maximal isometric contraction

Skin on the quadriceps muscles of the left leg was shaved and prepared to ensure that skin impedance was lower than 5 k Ω . Disposable surface electrodes (EL501, Biopac Systems Inc.) were positioned on the vastus medialis, rectus femoris and vastus lateralis with an intra pair distance of 20 mm, according to the method previously published (Rainoldi et al., 2004). Subjects performed two contractions at 25%, two contractions at 50% and two contractions at 75% of MVC (Drechsler et al., 2006) and electromyography (EMG) was assessed during maximal isometric knee extension. Surface electromyography was recorded with a three-way research system (MP150, Biopac Systems Inc.). The root mean square (RMS) method was used for smoothing with the Acq Knowledge software. EMG—force relationships were obtained from the values of the four contraction forces, using a linear regression model.

2.10|Statistical analysis

Statistical analyses were performed using StatView®. Each quantitative parameter was presented as mean \pm standard error of the mean (SEM) or as median and quartiles if normality was not verified. Descriptive analyses were carried out for subjects' characteristics and DOMS values. When appropriate, a repeated measures ANOVA or a Friedman ANOVA was performed. When tests found a significant interaction effect, a Tukey's or a pairwise Wilcoxon post hoc test was performed. A result was considered as significant when p value was lower than *0.05, **0.01 and ***0.001. To determine the meaningfulness of the effect of eccentric exercise, effect size (ES, Cohen's d) was calculated as the difference between pre- and post-exercise divided by the pooled standard deviation for maximal voluntary contraction force, maximal power output and integrated EMG signal (Cohen, 1988). According to the original Cohen's scale, effect sizes of 0.2, 0.5 and 0.8 were considered to be small, moderate and large effects.

3|RESULTS

3.1|Subjects

Characteristics of the 11 subjects are presented in Table 1. Briefly, mean age was 40.2 ± 4.0 years and mean body mass index (BMI) was 23.0 ± 0.7 kg.m⁻².

3.2|Tolerance to training: Heart rate frequency, RPE, delayed onset muscle soreness

Subjects were highly compliant with training procedures, easily performed reverse pedalling and all exercises were well-tolerated. Heart rate (HR) at rest was 67 ± 1 bpm and during exercise, peak HR increased to 97 ± 1 bpm (Figure 2). Peak HR did not exceed 100 bpm. Mean increase was about 29 ± 1 bpm between resting and exercise.

The RPE is depicted on Figure 3a, and the familiarization session (Session 1) was not taken into account for data analysis. Inter-individual variability of perceived exertion was high for the same exercise, but values were consistent between sessions for the same subject. RPE significantly increased with speed in every training session. It remained low (<5/10) but increased when subjects had to brake to 70 rpm, the hardest task. No effect of training was observed on subjects' RPE under 60 rpm, but training significantly decreased RPE by approximately 17.5% when braking to 70 rpm. Moreover, global RPE for one entire session, including all exercise speeds, was significantly lower with training.

Mean power outputs (PO) are presented in Figure 3b. Workloads achieved during eccentric cycling were high no matter the exercise and study time-point, and significantly increased with speed. At the beginning of the study, mean value obtained was about 50 W and maximal value plateaued at 540 W. At the end of training, minimal value was close to 100 W and maximal value reached 700 W. Workload was significantly different in-between the sessions at 60 rpm (210.1 ± 38.5 W compared to 293.8 ± 19.7 W). No significant change was found at other speeds. Lower work reproducibility corresponded to the fastest speed. The relationships between PO and RPE during session 2 and 5 are depicted in Figure 3c. Slope of linear fitting curve significantly increased ($p < 0.001$, +139%) after training programme.

Six subjects experienced DOMS. As presented in Table 2, all sessions generated DOMS for 1 to 3 subjects. DOMS values remained low, as maximal score was 3. For each session, mean DOMS value was very low (<1), because most of the subjects did not feel any muscular or joint pain.

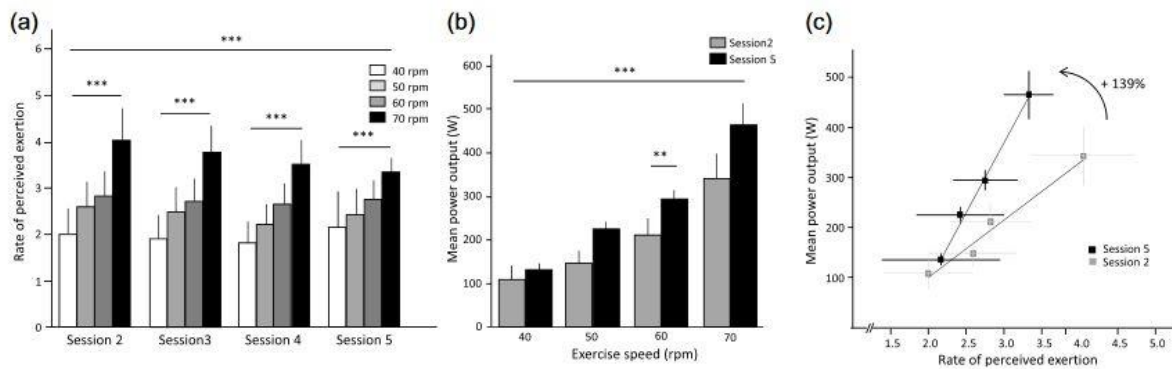


FIGURE 3 (a) Evolution of rate of perceived exertion (RPE) during the training programme at each exercise speed. (b) Eccentric power output data during the second and the fifth session at each exercise speed. (c) Evolution of the power output-RPE relationship between the second and the fifth session.

TABLE 2 Delayed Onset Muscle Soreness (DOMS) expressed in number of subjects with pain and minimal/maximal pain values

	Session 1	Session 2	Session 3	Session 4	Session 5
Subjects with DOMS	6				
	2	3	1	2	1
Minimum pain value	1	1	2	1	1
Maximum pain value	1	3	2	3	1

3.3|Effects on concentric sprint-cycling performance

Maximal power output was extracted from power-speed relationship (Figure4a). A third-order polynomial regression was used to fit all power-speed relationship curves. Training significantly increased maximal power output (Figure4b). Mean improvement was about 8.5%, corresponding to a 74W increase in the maximal power developed during sprints and a small effect size (ES = 0.25).

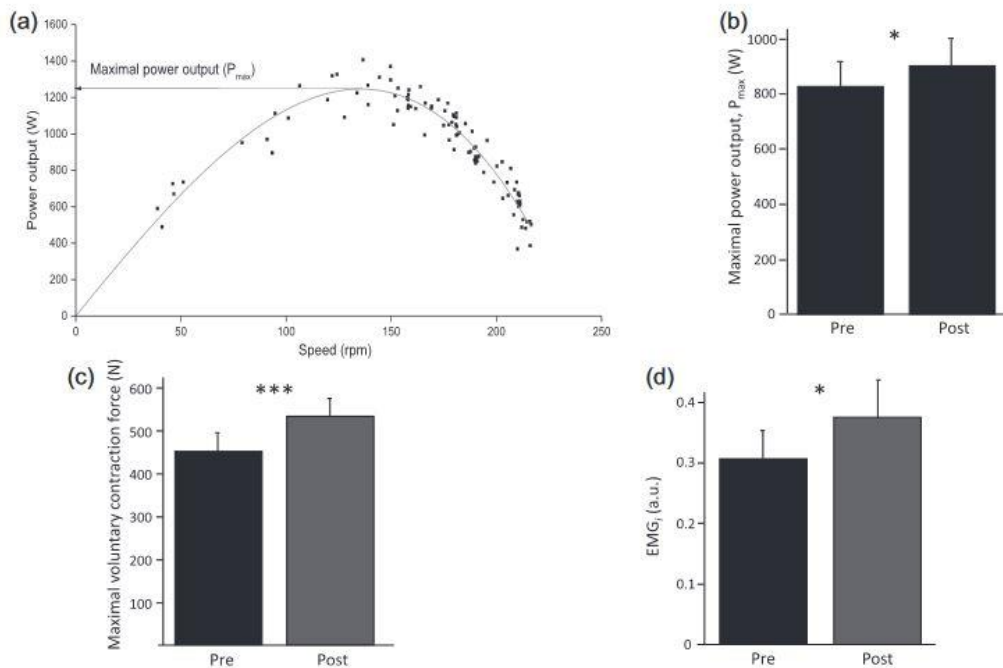


FIGURE 4 (a) Example of concentric power-speed relationship of one subject. Curve represents the third order polynomial regression used to extrapolate maximal power output (P_{max}). (b) Evolution of P_{max} before and after the training programme (ES = 0.25). (c) Evolution of maximal voluntary isometric contraction force (ES = 0.59) and (d) integrated EMG signal during isometric knee extension (ES = 0.55).

3.4|Effects on isometric contraction force

Results of MVC presented on Figure4c,d show that MVC significantly improved after training. Mean improvement was about 78N, corresponding to a 17% increase in force from baseline. Integrated EMG during MVC shows a significant increase (+22%) after training and a moderate effect size (ES = 0.59).

Relative EMG-Force relationship shifts above the curve obtained before the programme of eccentric cycling and the area under the EMG_i-Force curve was significantly increased by 5% after training ($p < 0.05$, ES = 0.55) (Figure5).

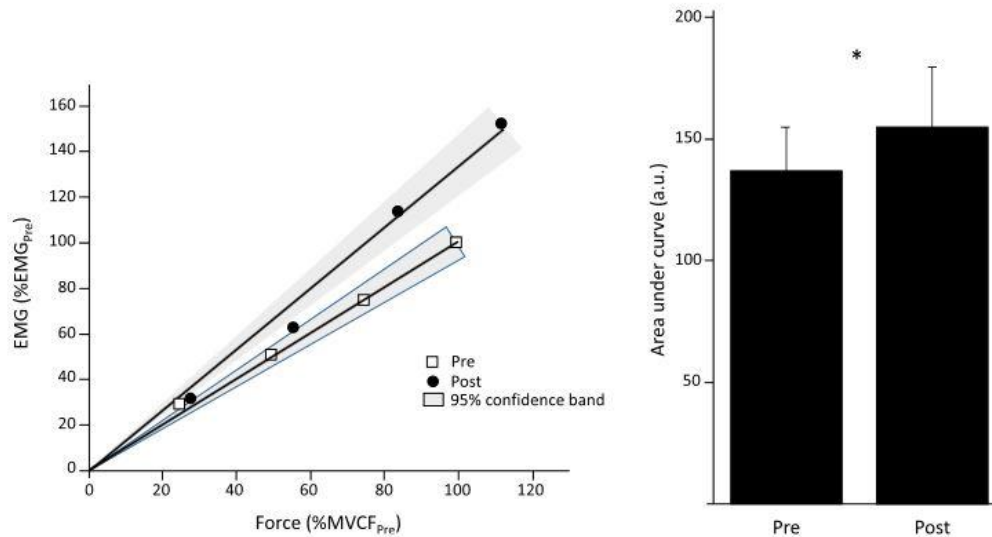


FIGURE 5 Left panel: example of EMGi-Force relationship curves for one subject before and after the training programme Right panel: evolution of area under the EMGi-Force curves before and after the training programme.

4|DISCUSSION

The ergometer was designed for hospital bed-cycling. Previously developed eccentric ergometers were developed for semi-recumbent practice (Elmer & Martin, 2013; Elmer et al., 2013; Hoppeler, 2016; Lewis, 2012; Rocha Vieira et al., 2011). Due to the stabilized position of the subjects in the bed, they had no difficulty to stay in a lying position with a minimal action of arms and trunk. Whereas in our study, healthy subjects could develop an intense mean power output near of 500W, in the literature patients with reduced physical capacity will develop noticeable lower power (Aagaard et al., 2010; Green et al., 2018; Hoppeler, 2016; Meyer et al., 2003), thus limiting upper body movement. With most of patients carrying a high cardiovascular risk as end-stage renal disease patients undergoing haemo-dialyses, the HR frequency increase during exercise must be limited. We report a modest 30 bpm increase, and peak HR did not exceed 100 bpm. Our results are in accordance with Chasland's study (Chasland et al., 2017), and consistent with previous observations (Lewis, 2012; Perrey et al., 2001). Power outputs reached in the present study were relatively high compared to classical concentric cycling exercise, extending the results of previous studies performed in a semi-recumbent position (P. C. Lastayo et al., 2000, 2003). Eccentric power outputs are rarely measured, workload being usually estimated from oxygen consumption or from a concentric performance (Laroche et al., 2013; Steiner et al., 2004). Compared to our data, power outputs were lower during familiarization sessions, due to lower rotation speeds

After five training sessions, participants achieved higher work-load for a given RPE. The relationship between PO and RPE was improved and gains were higher in eccentric (+29.6% in maximal eccentric PO) compared to isometric conditions (+17% in MVC) and were even greater compared to concentric type exercises (+8% in maximal concentric power). It was previously suggested that gains were specific to contraction mode and movement velocity (Roig et al., 2009). These functional gains specific to the eccentric type appear valuable in a clinical context since eccentric movements are required to support body weight, particularly during downhill activities to ensure balance and slow down. It was demonstrated that efficiency of eccentric training to decrease fall risk was at least equal (P. Lastayo et al., 2017)

or higher (P. C. Lastayo et al., 2003) to traditional concentric training by specifically improving eccentric strength. The transferability of strength gains after eccentric training is of major importance for frail patients. Major isometric strength gains following eccentric training were demonstrated (Julian et al., 2019; Roig et al., 2009) but to our knowledge, this is the first report of an increased MVC from the third week after only five training sessions in non-athletes. Similar values were found in a recumbent position with longer programmes (Lastayo et al., 2003, 2010, 2014). However, leg muscle power was shown to be a better determinant of physical performance than isometric strength (Bean et al., 2003; Reid & Fielding, 2012). Eccentric training in young individuals improved maximal cycling power after 8 weeks of training (Leong et al., 2014). In our study, maximal PO during sprints was significantly improved, extending previous results that early adaptive responses occur following eccentric exercise in a healthy population.

The force-EMGi relationship curve shifted above pretraining curve. As a 5% higher neural activation is involved to develop the same MVC after training, it indicates that a slight impairment in neuromuscular efficiency occurs during isometric contractions. Excitation-contraction coupling efficiency was previously shown to be transiently altered after training in eccentric condition, probably due to changes in membrane excitability, conduction velocity or impaired release of Ca^{2+} (Clos et al., 2021; Nasrabadi et al., 2018). However, here, the great isometric strength gains suggest that local nervous adaptations like an improved muscular recruitment exceed contractile function impairment. These results also mean that strength gains result in part from a neural drive optimization through a better motor units recruitment/a higher discharge rate of active motor units or from diminished inhibitory reflex loops. According to Kraemer, these improvements could also be related to the synchronized activation of agonistic, synergistic and antagonistic muscles (Kraemer et al., 1996). Motor learning could have improved neural drive of leg muscles to resist against the dynamometer, increasing production force capacity through an efficient activation of muscle involved in movement execution (Brueckner et al., 2018; Wulf et al., 2010).

In this study direct fatigue-related markers were not evaluated or measured, we used heart rate and RPE to evaluate exhaustion. RPE and neuromuscular fatigue were shown to be strongly correlated during endurance test (Cruz-Montecinos et al., 2019). Lastly, Zhao et al. (2022) provide evidence that RPE measure was efficient for muscle fatigue evaluation during resistance exercises (Zhao et al., 2022). As RPE provides perceptual difficulty, it was previously successfully used in frail population like elderly to assess indirect fatigue through perceptual training intensity (Morishita et al., 2018). Workload was progressively increased, but 6 subjects out of 11 subjects experienced moderated DOMS. They reported pain felt during daily eccentric movements like going downstairs. Subjects are differently sensitive to DOMS, and immobilized patients might be more fragile. There is no evidence that gender or age are determinants of DOMS sensitivity, but subjects performing downhill running and regular cycling did not report any pain whereas less active people were subjected to DOMS. These practices can induce a RBE and may explain the differential subjects' sensitivity. Some factors seem to promote DOMS and importance of speed was previously suggested (Hoppeler, 2016). Low velocity could be used to facilitate coordination and avoid damage. High velocities induce a disorganized muscular work in favour of a greater elastic component and joint solicitation (Elmer et al., 2010). Nevertheless, in other studies, subjects also experienced DOMS after the first session in a comparable extent of our group whereas rotation speed was below 60 rpm (Besson et al., 2013; Leong et al., 2014).

Workload has a major role and must be measured to ensure proper intensity and even though DOMS pain values were low, our programme can be improved. Our training procedures emerged from current recommendations, but most of the procedures are poorly described (Roig et al., 2008). As familiarization sessions are key steps to confer RBE, a periodization model was suggested to safely introduce eccentric (Harris-Love et al., 2017). Further studies conducted on healthy volunteers including these recommendations, controlling precisely workload and specially focused on DOMS, are needed to establish the mechanisms underpinning RBE and adequate eccentric intensity to avoid DOMS (Hyldahl et al., 2017). Although our study demonstrated the feasibility and effectiveness of eccentric exercise in the lying position, the application of such protocols on patients suffering from pathologies such as renal failure will require adaptations and further studies (Hoppeler, 2016; P. LaStayo et al., 2014). Indeed, the tolerance to exercise being strongly dependent on the concerned population, physiotherapy prescriptions will require a personalization of the physical training programmes with adapted familiarization sessions. The parameters to be adjusted may concern the intensity of the exercise, its duration or the number of repetitions per session. Another simple way to individualize exercise intensity would be to recommend an RPE to be achieved during exercise phases on the Borg scale.

5|CONCLUSION

In summary, our study shows that bed-cycling eccentric training is feasible, that adaptations to bed-cycling eccentric training occur in the early stage of practice and that strength and power gains following eccentric cycling are transferable to others contraction modalities, that is, concentric and isometric. Interestingly, most of the daily movements include an eccentric, a concentric and an isometric phase, and daily falls in frail people are most of the time attributable to a lack of balance during the eccentric phase. Eccentric movements are also prominent during downhill exercises like going down the stairs or sit on a seat, and the inability to brake the body weight considerably limits functional independence and quality of life. Thus, the specificity of eccentric regimen might constitute a promising exercise mode not only to fight against muscle atrophy linked to end-stage renal disease but also for many clinical applications as haemo-dialyses since training can be safely perform in a lying position and is efficient on muscle function improvement. Transferability of gains to concentric and isometric modalities will allow to improve whole leg function and positively impacts physical abilities in healthy and frail populations.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

- Aagaard, P., Suetta, C., Caserotti, P., Magnusson, S.P. & Kjær, M. (2010) Role of the nervous system in sarcopenia and muscle atrophy with aging: strength training as a counter measure. *Scandinavian Journal of Medicine and Science in Sports*, 20(1), 49–64. <https://doi.org/10.1111/j.1600-0838.2009.01084.x>
- Abbott, B.C., Bigland, B. & Ritchie, J.M. (1952) The physiological cost of negative work. *The Journal of Physiology*, 117, 380–390.
- Arsac, L.M., Belli, A. & Lacour, J. (1996) Muscle function during brief maximal exercise: accurate measurements on a friction-loaded cycle ergometer. *European Journal of Applied Physiology and Occupational Physiology*, 74, 100–106.
- Astrand, P.O. & Saltin, B. (1961) Maximal oxygen uptake and heart rate in various types of muscular activity. *Journal of Applied Physiology*, 16, 977–981.
- Bean, J.F., Leveille, S.G., Kiely, D.K., Bandinelli, S., Guralnik, J.M. & Ferrucci, L. (2003) A comparison of leg power and leg strength within the In CHIANTI study: which influences mobility more? *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, 58A(8), 728–733.
- Besson, D., Joussain, C., Gremeaux, V., Morisset, C., Laurent, Y., Casillas, J.M. et al. (2013) Eccentric training in chronic heart failure: feasibility and functional effects. Results of a comparative study. *Annals of Physical and Rehabilitation Medicine*, 56(1), 30–40. <https://doi.org/10.1016/j.rehab.2013.01.003>
- Bigland-Ritchie, B. & Woods, J.J. (1976) Integrated electromyogram and oxygen uptake during positive and negative work. *The Journal of Physiology*, 260, 267–277.
- Bordoni, B. & Varacallo, M. (2022) Anatomy, bony pelvis and lower limb, thigh quadriceps muscle. StatPearls [Internet]. Treasure Island (FL): Stat Pearls Publishing.
- Brown, M., Sinacore David, R. & Host Helen, H. (1995) The relationship of strength to function in the older adult. *The Journals of Gerontology*, 50A, 55–59. <https://biomedgerontology.oxfordjournals.org/>
- Brueckner, D., Kiss, R. & Muehlbauer, T. (2018) Associations between practice-related changes in motor performance and muscle activity in healthy individuals: a systematic review. *Sports Medicine*, 48(1), 9. <https://doi.org/10.1186/s40798-018-0123-6>
- Chasland, L.C., Green, D.J., Maiorana, A.J., Nosaka, K., Haynes, A., Dembo, L.G. et al. (2017) Eccentric cycling: a promising modality for patients with chronic heart failure. *Medicine & Science in Sports & Exercise*, 49(4), 646–651. <https://doi.org/10.1249/MSS.00000-00000001151>

Chen, T.C.C., Tseng, W.C., Huang, G.L., Chen, H.L., Tseng, K.W. & Nosaka, K. (2017) Superior effects of eccentric to concentric knee extensor resistance training on physical fitness, insulin sensitivity and lipid profiles of elderly men. *Frontiers in Physiology*, 8, 209. <https://doi.org/10.3389/fphys.2017.00209>

Clos, P., Mater, A., Laroche, D. & Lepers, R. (2021) Concentric versus eccentric cycling at equal power output or effort perception: neuromuscular alterations and muscle pain. *Scandinavian Journal of Medicine & Science in Sports*, 32, 45–59. <https://doi.org/10.1111/sms.14053>

Cohen, J. (1988) *Statistical power analysis for the behavioral sciences* second edition. <https://doi.org/10.4324/9780203771587>

Čretnik, K., Pleša, J., Kozinc, Ž., Löfler, S. & Šarabon, N. (2022) The effect of eccentric vs. traditional resistance exercise on muscle strength, body composition, and functional performance in older adults: a systematic review with meta-analysis. *Frontiers in Sports and Active Living*, 4, 873718. <https://doi.org/10.3389/fspor.2022.873718>

Cruz-Montecinos, C., Bustamante, A., Candia-González, M., González-Bravo, C., Gallardo-Molina, P., Andersen, L.L. et al. (2019) Perceived physical exertion is a good indicator of neuromuscular fatigue for the core muscles. *Journal of Electromyography and Kinesiology*, 49, 102360. <https://doi.org/10.1016/j.jelekin.2019.102360>

Douglas, J., Pearson, S., Ross, A. & McGuigan, M. (2017) Chronic adaptation to eccentric training: a systematic review. *Sports Medicine*, 47(5), 917–941. <https://doi.org/10.1007/s40279-016-0628-4>

Drechsler, W.I., Cramp, M.C. & Scott, O.M. (2006) Changes in muscle strength and EMG median frequency after anterior cruciate ligament reconstruction. *European Journal of Applied Physiology*, 98, 613–623. <https://doi.org/10.1007/s00421-006-0311-9> Elmer, S.J.,

Danvind, J. & Holmberg, H.-C. (2013) Development of a novel eccentric arm cycle ergometer for training the upper body. *Medicine & Science in Sports & Exercise*, 45, 206–211. <https://doi.org/10.1249/MSS.0b013e318269c79c>

Elmer, S.J., Madigan, M.L., LaStayo, P.C. & Martin, J.C. (2010) Joint-specific power absorption during eccentric cycling. *Clinical Biomechanics*, 25(2), 154–158. <https://doi.org/10.1016/j.clinbiomech.2009.10.014>

Elmer, S.J. & Martin, J.C. (2013) Construction of an isokinetic eccentric cycle ergometer for research and training. *Journal of Applied Biomechanics*, 29(4), 490–495

Flythe, J.E., Chang, T.I., Gallagher, M.P., Lindley, E., Madero, M., Sarafidis, P.A. et al. (2020) Blood pressure and volume management in dialysis: conclusions from a kidney disease: improving global outcomes (KDIGO) controversies conference. *Kidney International*, 97(5), 861–876. <https://doi.org/10.1016/j.kint.2020.01.046>

Gardner, A.S., Stephens, S., Martin, D.T., Lawton, E., Lee, H. & Jenkins, D. (2004) Accuracy of SRM and power tap power monitoring systems for bicycling. *Medicine & Science in Sports & Exercise*, 36(7), 1252–1258. <https://doi.org/10.1249/01.MSS.0000132380.21785.03>

Garnier, Y.M., Lepers, R., Canepa, P., Martin, A. & Paizis, C. (2022) Effect of the knee and hip angles on knee extensor torque: neural, architectural, and mechanical considerations. *Frontiers in Physiology*, 12, 789867. <https://doi.org/10.3389/fphys.2021.789867>

Gollie, J.M., Patel, S.S., Scholten, J.D. & Harris-love, M.O. (2020) Preliminary study of the effects of eccentric-overload resistance exercise on physical function and torque capacity in chronic kidney disease. *Journal of Functional Morphology and Kinesiology*, 5, 97. www.mdpi.com/journal/jfmk

Goulding, R.P., Marwood, S., Okushima, D., Poole, D.C., Barstow, T.J., Lei, T.H. et al. (2020) Effect of priming exercise and body position on pulmonary oxygen uptake and muscle deoxygenation kinetics during cycle exercise. *Journal of Applied Physiology*, 129, 810–822. <https://doi.org/10.1152/jappphysiol.00478.2020.-We>

Green, D.J., Thomas, K., Ross, E.Z., Green, S.C., Pringle, J.S.M. & Howatson, G. (2018) Torque, power and muscle activation of eccentric and concentric isokinetic cycling. *Journal of Electromyography and Kinesiology*, 40, 56–63. <https://doi.org/10.1016/j.jelekin.2018.03.005>

Harris-Love, M.O., Seamon, B.A., Gonzales, T.I., Hernandez, H.J., Pennington, D. & Hoover, B.M. (2017) Eccentric exercise program design: a periodization model for rehabilitation applications. *Frontiers in Physiology*, 8(February), 116. <https://doi.org/10.3389/fphys.2017.00112>

Harrison, A.J., Burdon, C.A., Groeller, H. & Peoples, G.E. (2020) The acute physiological responses of eccentric cycling during the recovery periods of a high intensity concentric cycling interval session. *Frontiers in Physiology*, 11, 336. <https://doi.org/10.3389/fphys.2020.00336>

Hoppeler, H. (2016) Moderate load eccentric exercise; a distinct novel training modality. *Frontiers in Physiology*, 7(NOV), 483. <https://doi.org/10.3389/fphys.2016.00483>

Hyldahl, R.D., Chen, T.C. & Nosaka, K. (2017) Mechanisms and mediators of the skeletal muscle repeated bout effect. *Exercise and Sport Sciences Reviews*, 45(1), 24–33. <https://doi.org/10.1249/JES.0000000000000095>

Johansen, K.L. (2008) Exercise and dialysis. *Hemodialysis International*, 12, 290–300. Jones, A.M., Berger, N.J.A., Wilkerson, D.P. & Roberts, C.L. (2006) Effects of “priming” exercise on pulmonary O₂ uptake and muscle deoxygenation kinetics during heavy-intensity cycle exercise in the supine and upright positions. *Journal of Applied Physiology*, 101, 1432–1441. <https://doi.org/10.1152/jappphysiol.00436.2006.-We>

Julian, V., Thivel, D., Miguet, M., Pereira, B., Costes, F., Coudeyre, E. et al. (2019) Eccentric cycling is more efficient in reducing fat mass than concentric cycling in adolescents with obesity. *Scandinavian Journal of Medicine & Science in Sports*, 29(1), 4–15. <https://doi.org/10.1111/sms.13301>

Kraemer, W.J., Fleck, S.J. & Evans, W.J. (1996) Strength and power training: physiological mechanisms of adaptation. *Exercise and Sport Sciences Reviews*, 24, 363–398.

Laroche, D., Joussain, C., Espagnac, C., Morisset, C., Tordi, N., Gremeaux, V. et al. (2013) Is it possible to individualize intensity of eccentric cycling exercise from perceived exertion on concentric test? *Archives of Physical Medicine and Rehabilitation*, 94(8),1621–1627.<https://doi.org/10.1016/j.apmr.2012.12.012>

LaStayo, P., Marcus, R., Dibble, L., Frajacomo, F. & Lindstedt, S. (2014) Eccentric exercise in rehabilitation: safety feasibility, and application. *Journal of Applied Physiology*, 116(11), 1426–1434.<https://doi.org/10.1152/jappphysiol.00008.2013>

Lastayo, P., Marcus, R., Dibble, L., Wong, B. & Pepper, G. (2017) Eccentric versus traditional resistance exercise for older adult fallers in the community: a randomized trial within a multi-component fall reduction program. *BMC Geriatrics*, 17(149), 149.<https://doi.org/10.1186/s12877-017-0539-8>

Lastayo, P.C., Ewy, G.A., Pierotti, D.D., Johns, R.K. & Lindstedt, S. (2003) The positive effects of negative work: increased muscle strength and decreased fall risk in a frail elderly population. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, 58A(5),M419–M424.<https://doi.org/10.1093/gerona/58.5.M419>

LaStayo, P.C., Larsen, S., Smith, S., Dibble, L. & Marcus, R. (2010) The feasibility and efficacy of eccentric exercise with older cancer survivors: a preliminary study. *Journal of geriatric physical therapy*,33(3), 135–140.<https://doi.org/10.1097/JPT.0b013e3181eda45e>

Lastayo, P.C., Pierotti, D.J., Pifer, J., Hoppeler, H. & Lindstedt, S.L. (2000) Eccentric ergometry: increases in locomotor muscle size and strength at low training intensities. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology*, 278, 1282–1288.

Leong, C., Mc Dermott, W., Elmer, S. & Martin, J. (2014) Chronic eccentric cycling improves quadriceps muscle structure and maximum cycling power. *International Journal of Sports Medicine*, 35, 559–565.

Leszczak, T.J., Olson, J.M., Stafford, J. & Brezzo, R.D. (2013) Early adaptations to eccentric and high-velocity training on strength and functional performance in community-dwelling older adults. *Journal of Strength and Conditioning Research*, 27(2), 442–448. Lewis, M.C. (2012). The feasibility of eccentric cycling as a training modality for increasing quadriceps strength at low cardiovascular cost.

Lewis, M.C., Peoples, G.E., Groeller, H. & Brown, M.A. (2018) Eccentric cycling emphasising a low cardiopulmonary demand increases leg strength equivalent to workload matched concentric cycling in middle age sedentary males. *Journal of Science and Medicine in Sport*,21(12), 1238–1243.<https://doi.org/10.1016/j.jsams.2018.05.009>

Lin, M.-J., Chen, T.C.-C., Chen, H., Wu, B.-H. & Nosaka, K. (2015) Muscle damage protection by low-intensity eccentric contractions for the knee extensors and flexors. *Applied Physiology, Nutrition, and Metabolism*, 40, 1–36.

Macdonald, M.J., Kevin Shoemaker, J., Tschakovsky, M.E., Hughson, R.L., Tschakovsky, M.E. & Hughson Alveo, R.L. (1998) Alveolar oxygen uptake and femoral artery blood flow dynamics in upright and supine leg exercise in humans. <https://www.jap.org>

Magnusson, S.P. & Kjaer, M. (2019) The impact of loading, unloading, ageing and injury on the human tendon. *The Journal of Physiology*, 597(5), 1283–1298. <https://doi.org/10.1113/JP275450>

McCormack, H.M., de L. Horne, D.J. & Sheather, S. (1988) Clinical applications of visual analogue scales: a critical review. *Psychological Medicine*, 18, 1007–1019. <https://doi.org/10.1017/S0033291700009934>

McHugh, M.P. (2003) Recent advances in the understanding of the repeated bout effect: the protective effect against muscle damage from a single bout of eccentric exercise. *Scandinavian Journal of Medicine & Science in Sports*, 13, 88–97.

Meyer, K., Steiner, R., Lastayo, P., Lippuner, K., Allemann, Y., Eberli, F. et al. (2003) Eccentric exercise in coronary patients: central hemodynamic and metabolic responses. *Medicine & Science in Sports & Exercise*, 35(7), 1076–1082. <https://doi.org/10.1249/01.MSS.0000074580.79648.9D>

Morishita, S., Tsubaki, A., Takabayashi, T. & Fu, J.B. (2018) Relationship between the rating of perceived exertion scale and the load intensity of resistance training. *Strength & Conditioning Journal*, 40(2), 94–109. <https://doi.org/10.1519/SSC.0000000000000373>

Nasrabadi, R., Izanloo, Z., Sharifnezhad, A., Hamedinia, M.R. & Hedayatpour, N. (2018) Muscle fiber conduction velocity of the vastus medialis and lateralis muscle after eccentric exercise induced-muscle damage. *Journal of Electromyography and Kinesiology*, 43, 118–126. <https://doi.org/10.1016/j.jelekin.2018.06.008>

Oranchuk, D.J., Storey, A.G., Nelson, A.R. & Cronin, J.B. (2019) Scientific basis for eccentric quasi-isometric resistance training: a narrative review. *Journal of Strength and Conditioning Research*, 33(10), 2846–2859.

Painter, P., Carlson, L., Carey, S., Paul, S.M. & Myll, J. (2000) Physical functioning and health-related quality-of-life changes with exercise training in hemodialysis patients. *American Journal of Kidney Diseases*, 35(3), 482–492.

Pavlin, L., Rodriguez, A., Ohresser, I., Larivière, M., Portal, C., Cristol, J. et al. (2022) Does the interference phenomenon affect strength development during same-session combined rehabilitation program in hemodialysis patients? *Seminars in Dialysis*, 35(2), 154–164. <https://doi.org/10.1111/sdi.13033>

Perrey, S., Betik, A., Candau, R., Rouillon, J.D. & Hughson, R.L. (2001) Comparison of oxygen uptake kinetics during concentric and eccentric cycle exercise. *Journal of Applied Physiology*, 91, 2135–2142.

Proske, U. & Morgan, D.L. (2001) Muscle damage from eccentric exercise: mechanism, mechanical signs, adaptation and clinical applications. *The Journal of Physiology*, 537(2), 333–345. <https://doi.org/10.1111/j.1469-7793.2001.00333.x>

Rainoldi, A., Melchiorri, G. & Caruso, I. (2004) A method for positioning electrodes during surface EMG recordings in lower limb muscles. *Journal of Neuroscience Methods*, 134, 37–43.<https://doi.org/10.1016/j.jneumeth.2003.10.014>

Reid, K.F. & Fielding, R.A. (2012) Skeletal muscle power. *Exercise and Sport Sciences Reviews*, 40(1), 4–12.<https://doi.org/10.1097/jes.0b013e31823b5f13>

Rocha Vieira, D.S., Baril, J., Richard, R., Perrault, H., Bourbeau, J. & Taivassalo, T. (2011) Eccentric cycle exercise in severe COPD :feasibility of application. *COPD: Journal of Chronic Obstructive Pulmonary Disease*, 8, 270274.<https://doi.org/10.3109/15412555.2011.579926>

Roig, M., O'Brien, K., Kirk, G., Murray, R., McKinnon, P., Shadgan, B. et al.(2009) The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: a systematic review with meta-analysis. *British Journal of Sports Medicine*, 43(8),556–568.<https://bjsm.bmj.com/content/43/8/556.abstract>

Roig, M., Shadgan, B. & Reid, W.D. (2008) Eccentric exercise in patients with chronic health conditions: a systematic review. *Physiotherapy Canada*, 60(2), 146–160.<https://doi.org/10.3138/physio.60.2.146>

Souweine, J.S., Boudet, A., Chenine, L., Leray, H., Rodriguez, A., Mourad, G. et al. (2017) Standardized method to measure muscle force at the bedside in hemodialysis patients. *Journal of Renal Nutrition*, 27(3), 194–200.<https://doi.org/10.1053/j.jrn.2017.01.017>

Steiner, R., Meyer, K., Lippuner, K., Schmid, J.P., Saner, H. & Hoppeler, H.(2004a) Eccentric endurance training in subjects with coronary artery disease: a novel exercise paradigm in cardiac rehabilitation? *European Journal of Applied Physiology*, 91(5–6), 572–578.<https://doi.org/10.1007/s00421-003-1000-6>

Vale, R.D. & Milligan, R.A. (2000) The way things move: looking under the hood of molecular motor proteins. *Science*, 288(April), 88–95.

Vogt, M. & Hoppeler, H.H. (2014) Eccentric exercise: mechanisms and effects when used as training regime or training adjunct. *Journal of Applied Physiology*, 116(11), 1446–1454.<https://doi.org/10.1152/jappphysiol.00146.2013>

Wehrle, A., Waibel, S., Gollhofer, A. & Roecker, K. (2021) Power output and efficiency during supine, recumbent, and upright cycle ergometry. *Frontiers in Sports and Active Living*, 3, 667564.<https://doi.org/10.3389/fspor.2021.667564>

Westhoff, M.H., Stemmerik, L. & Boshuizen, H.C. (2000) Effects of a low-intensity strength-training program on knee-extensor strength and functional ability of frail older people. *Journal of aging and physical activity*, 8, 325–342.

Williams, N. (2017) The borg rating of perceived exertion (RPE) scale. *Occupational Medicine*, 67, 404–405.<https://doi.org/10.1093/occmed/kqx063>

Wulf, G., Shea, C. & Lewthwaite, R. (2010) Motor skill learning and performance: a review of influential factors. *Medical Education*, 44,75–84.<https://doi.org/10.1111/j.1365-2923.2009.03421.x>

Zhao, H., Nishioka, T. & Okada, J. (2022) Validity of using perceived exertion to assess muscle fatigue during resistance exercises. *PeerJ*, 10, e13019.<https://doi.org/10.7717/peerj.13019>