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Physiological Responses to Counterweighted Single-Leg Cycling in Older Males

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ABSTRACT

International Journal of Exercise Science 13(2): 1487-1500, 2020. Single-leg cycling (SLC) allows for a greater muscle specific exercise capacity and therefore provides a greater stimulus for metabolic and vascular adaptations compared to double-leg cycling (DLC). The purpose of this investigation was to compare the cardiovascular, peripheral, and metabolic responses of counterweighted (10kg) SLC to DLC in a healthy older male population. Eleven males (56-86 years) performed two cycling modalities consisting of DLC and SLC. For each modality, participants performed 4-minute cycling trials (60rpm) at three work rates (25, 50, 75W). Repeated measures ANOVAs and paired samples T-test (α=0.05) were used to assess differences in physiological and perceptual responses. Heart rate (100±21 vs. 103±20bpm), oxygen uptake (12.1±3.6 vs. 11.7±2.8mL*kg^{-1}*min^{-1}) and mean arterial pressure (104±13 vs. 108±12mmHg) were not different between DLC and SLC, respectively. Femoral blood flow was greater during SLC at 50W (741.4±290.3 vs. 509.0±230.8mL/min) and 75W (993.8±236.2 vs. 680.6±278.0mL/min) ($p\leq0.01$). Furthermore, carbohydrate oxidation during SLC was 30-40% greater than DLC across work rates ($p\leq0.011$). Whole body rating of perceived exertion (RPE) at 25 and 50W were not different ($p=0.065$), however, whole body RPE at 75W and leg RPE were higher for SLC at all intensities ($p\leq0.018$). Liking scores were not different between cycling modalities ($p=0.060$). At low and moderate intensities, SLC provides a greater peripheral stress with no difference in cardiovascular responses compared to DLC in a healthy older adult male population. Thus, SLC may be a feasible exercise modality to maximize peripheral adaptations for healthy and diseased (i.e. peripheral vascular disease/cardiovascular disease) older population.

KEY WORDS: Blood flow, exercise, oxygen uptake, skeletal muscle

INTRODUCTION

High-intensity endurance training results in greater improvements in skeletal muscle adaptations (33), maximum oxygen uptake (15), and aerobic performance (15) when compared to lower intensity training. However, the elevated cardiovascular risk associated with the high cardiovascular load during intense whole-body exercise may preclude its use for the older or diseased populations. Furthermore, during high-intensity whole-body exercise, blood flow to the active muscles is limited by central circulation (23,29,30) and the arterial baroreceptor maintenance of blood pressure at the expense of skeletal muscle blood flow (6,25). However, exercise involving smaller muscle mass can maximize the muscle specific exercise intensity resulting in greater positive adaptations while minimizing strain on the cardiovascular system.

Previous investigators have employed single-leg cycling (SLC) as an aerobic exercise modality and reported that SLC can generate greater leg specific work rates when compared to double-leg cycling (DLC) (2,9,11,20,28). Specifically, SLC confines the exercise to a smaller muscle mass resulting in greater limb specific blood flow (i.e. blood flow is no longer 'shared' by both legs) (5) which allows the participant to exercise at much greater limb specific intensity or for a longer duration at similar limb specific intensity. While research supports the use of SLC to generate greater leg specific work rates, the biomechanics of SLC on a traditional cycler ergometer is very different than the biomechanics of DLC, making the exercise awkward and uncomfortable. SLC requires the recruitment of the fatigable hip flexors during the upstroke of the pedal cycle, thus limiting the application of SLC as an exercise modality. To overcome this limitation, previous investigators have either used a motor (18) or a fixed gear ergometer to facilitate smooth SLC biomechanics (9,10). More recently a counterweight was mounted on the non-occupied crank arm such that the counterweight assists with the upward phase of the active limb and thereby reducing the need to recruit hip flexors (1,5,12,21). The results indicated that, at least in the young healthy population, the counterweighted SLC allows for greater limb specific exercise intensity without additional cardiovascular stress (5). It has yet to be determined how older adults or diseased individuals will respond to SLC with a counterweight.

The purpose of this investigation was to determine if older adults could tolerate/coordinate SLC that is assisted with a counterweight and to compare the cardiovascular responses between double-leg and counterweighted SLC in the older population. Based on previous results, we hypothesized that SLC with a counterweight will be well tolerated in an older population and will generate similar cardiovascular responses and rating of perceived exertion (RPE) compared to DLC. However, we also hypothesized that the metabolic responses and blood flow to the working limb would be greater during SLC compared to DLC.

METHODS

Participants

Eleven healthy older men (age 66 ± 8, 56-86 years; body mass 87.5 ± 13.5 kg; height 182 ± 5 cm) volunteered to participate in the study. Individuals with pulmonary or cardiovascular disease, neuro-muscular impairment or any condition that would limit their ability to complete the exercises safely were excluded from this investigation. Initially, participants were informed about the risks and benefits of the study. An informed consent, health history questionnaire and physician's clearance to participate was obtained prior to inclusion into the study. Furthermore, all procedures were reviewed and approved by the Kent State University Institutional Review Board. This research was carried out fully in accordance to the ethical standards of the International Journal of Exercise Science (24).

Table 1. Physical characteristics of participants at inclusion.

Age (years)	66 ± 8
Height (cm)	182 ± 5
Body Mass (kg)	87.5 ± 13.5
Body Mass Index (kg/m^2)	26.5 ± 3.8
Mean Arterial Pressure (mmHg)	92 ± 11
Systolic Blood Pressure (mmHg)	122 ± 17
Diastolic Blood Pressure (mmHg)	77 ± 9
Heart Rate (bpm)	73 ± 15
Femoral Blood Flow (mL/min)	140.1 ± 69.7
Estimated VO_2max (mL*kg^{-1}*min^{-1})	33.4 ± 4.9

Protocol

During the initial visit, a series of baseline measurements were obtained from the participants (Table 1). These measurements included: height, weight, resting blood pressure (manual aneroid sphygmomanometer), resting heart rate (HR), and femoral artery blood flow (FBF) utilizing a GE Logiq 7 Doppler /ultrasound (GE Healthcare Milwaukee, Wisconsin- *see details of blood flow measurement below*). Following these measurements, the participant performed a YMCA submaximal cycle ergometry test (14) to estimate aerobic capacity. In brief, a modified ramp protocol was used that included a standard first stage of 150 kpm/min and then 2-1 additional stages in which the workload was based on HR responses to the initial stage. The linear relationship between HR (greater than 110) and workload was then extrapolated to estimated max heart rate to predict maximum power output and associated oxygen uptake (VO_2). After completing the YMCA submaximal cycling protocol, participants were familiarized with counterweighted SLC.

The experimental cycling protocol required participants to pedal a Monark Ergomedic 828E cycle ergometer (Monark Exercise AB, Vansbro, Sweden) across two cycling modalities: traditional DLC and SLC. The SLC modality used a 10kg counterweight placed on the unoccupied crank arm of the ergometer. The purpose of the counterweight was to help assist the active limb back to the top of the pedal stroke; this reduced the need to recruit hip flexor muscles, thus better resembling the biomechanics of standard DLC (13). During SLC, the right leg performed cycling exercise while the non-active left leg remained at rest was supported by a wooden box on the side of the ergometer.

Within each cycling modality the participants completed 4-minute cycling trials (60rpm) at three different work rates (25, 50, and 75 W) totaling 12 minutes of cycling. Cycling modalities were counterbalanced to eliminate an order effect and a 10-minute recovery period separated the two cycling modalities. Prior to the second bout of cycling, HR and blood pressure were recorded to ensure they returned to resting levels. Although the total work rate remained the same across both modalities, the active right limb during the SLC modality performed twice as much work as it did during the DLC modality: work performed during DLC was divided across two active legs.

During the cycling protocols participants wore a HR monitor (Suunto, Vantaa, Finland) that transmitted data to a Schoberer Rad Messtechenik (SRM) power meter 7, which measured and recorded power (Colorado Springs, Colorado, USA). A Parvo Medics True One 2400 metabolic cart (Parvo Medics, Salt Lake City, UT) was used to measure VO_2 and RER during the exercise trials. During the last 30 seconds of each work rate mean arterial pressure (MAP) was manually measured by a trained technician using an aneroid sphygmomanometer and participants were asked to report their total body RPE as well as leg specific RPE using the Borg (6-20) RPE scale (3). Upon completion of each cycling modality, participants were asked to indicate their liking of the exercise using a Visual Analog Scale. Specifically, participants to place an X on a 10cm line, with the far left marked "did not like at all", the middle with "neutral", and the far right with "liked a lot" (7,22). VO2, carbon dioxide production (VCO_2) and RER were recorded for the last minute of each cycling workload. Carbohydrate oxidation was calculated in grams per liter of oxygen using the equation, $1.695 * VO_2 - 1.701 * VCO_2$ (26).

Femoral Blood Flow: A Logiq 7 GE ultrasound Doppler and linear M12 transducer (GE Healthcare, New York, NY) was used to assess both resting and exercise FBF. Specifically, FBF was measured during the initial visit, prior to the start and immediately following the completion of each cycling stage while the subject was seated on the cycle ergometer. At the completion of each 4-minute stage, participants were asked to stop cycling and immediately extend the right leg while remaining seated on the stationary cycle so that an ultrasound transducer could be placed above the right femoral artery. Diameter and angle corrected and intensity -weighted mean blood velocity (Vmean) were measured for 15 s. Following the measurement subjects resumed peddling to start the next stage. In total, subjects remained stopped for less than 30 seconds between stages to allow for blood flow measurements. Consistent and timely probe placement (within 3-4 seconds following pedaling termination) was made possible by marking the location for probe placement on the skin prior to testing. Ultimately, blood flow data for two subjects was not included in the results due to difficulty in obtaining Doppler images following cessation of cycling. FBF was ultimately calculated as: Blood Flow (mL/min) = $radius^2 * 3.14 * Vmean * 60$. Vascular conductance was then calculated as: FBF/MAP (16).

Statistical Analysis

The dependent variables assessed were VO_2, HR, MAP, RER, carbohydrate oxidation, FBF, vascular conductance, whole body RPE, leg RPE and liking score. Statistical analysis for liking scores was performed using a paired sample T-Test. For all other variables, after passing assumptions for normality, statistical analysis was performed using two-way repeated measures ANOVA on cycling modality (DLC and SLC) and work rate (25, 50, 75 W) followed by a Benjamini-Hochberg post-hoc correction using SPSS software (SPSS version 22, SPSS Inc., Chicago Illinois). The level of significance was set at $p \leq 0.05$. All data are reported as mean ± SD. Our sample size was based on our previous publication (5) revealed an effect size of 1.2 and observed power of 0.93 required only 8 subjects, however initially increased our recruitment due to this study being conducted on older individuals that might be more heterogeneous.

RESULTS

Cardiovascular Responses: There was a main effect of work rate on HR ($F=66.41$; $p=<0.001$; $ES=0.869$) but not cycling modality ($F=3.11$; $p=0.109$) nor their interaction ($F=0.381$; $p=0.688$) (Figure 1A). There was also a main effect of work rate ($F=10.49$; $p=0.009$; $ES=0.821$) and cycling modality ($F=36.44$; $p<0.001$; $ES=0.512$) on MAP but there was no significant interaction ($F=0.091$; $p=.913$). Despite the significant main effect of cycling modality on MAP (SLC=107.8±12.1 and DLC=104.5±12.9 mmHg) post hoc failed to indicate a significant difference in MAP at any specific work rate ($p\geq0.055$) (Figure 1B). With regards to VO_2, there was a main effect of work rate ($F=117.4$; $p<0.001$; $ES=0.912$) but not cycling modality ($F=1.30$; $p=0.282$). The analysis did reveal a significant interaction of work rate and cycling modality ($F=8.21$; $p=0.002$; $ES=0.451$) on VO_2 (Figure 1C).

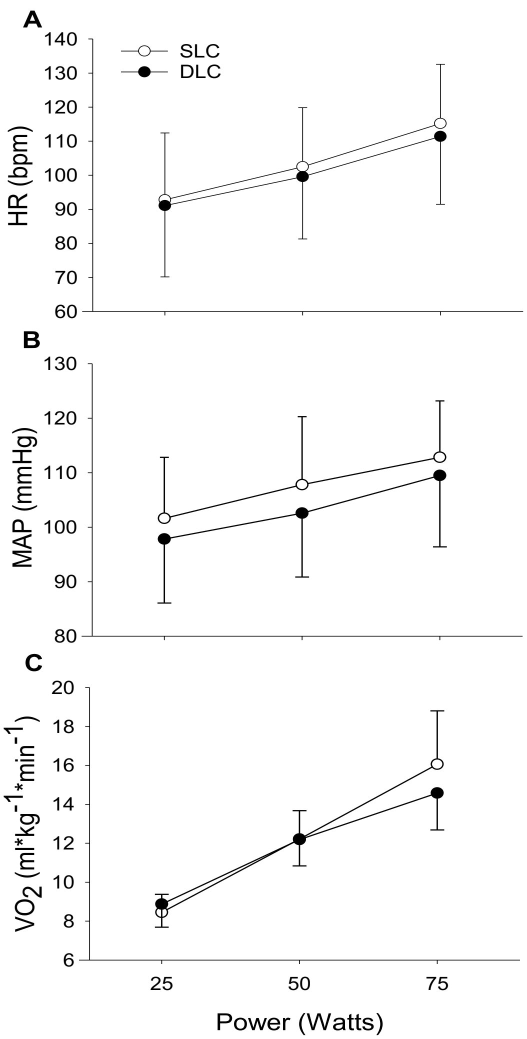

Figure 1. HR, MAP, and VO_2 during single-leg cycling (SLC) and double-leg cycling (DLC) across three work rates. There was a main effect of work rate for HR, MAP, and VO_2.

Blood Flow Responses: FBF (n=9) at baseline was 140.1 ± 69.7 mL/min and increased to a max of 923.9 ± 302.8 and 609.0 ± 285.4 mL/min for the SLC and DLC, respectively. There was a main effect of work rate (F=34.41; p<0.001; ES=0.811), cycling modality (F=29.74; p=0.001; ES=0.788) as well as their interaction on FBF (F=6.10; p=0.010; ES=0.44). Post hoc comparisons revealed FBF during SLC was greater than DLC for 50W (p=0.015: ES=0.68) and 75W (p=0.003; ES 0.90) but there was no difference at 25W (p= 0.09) (Figure 2A). Furthermore, we examined vascular conductance to determine if increases in FBF were strictly related to changes in blood pressure or changes in peripheral vasodilation. Similar to FBF there was a main effect of cycling modality (F=25.54; p=0.001; ES=0.78), work rate (F=31.0; p<0.001; ES=0.781) as well as their interaction (F=5.85; p=0.012; ES=0.31) on vascular conductance. Paired t-tests revealed that vascular conductance was significantly greater during SLC compared to DLC at 50W (p=0.018; ES=0.65) and 75W (p=0.003; ES=0.65), however, there was no difference at 25W (p=0.115) (Figure 2B).

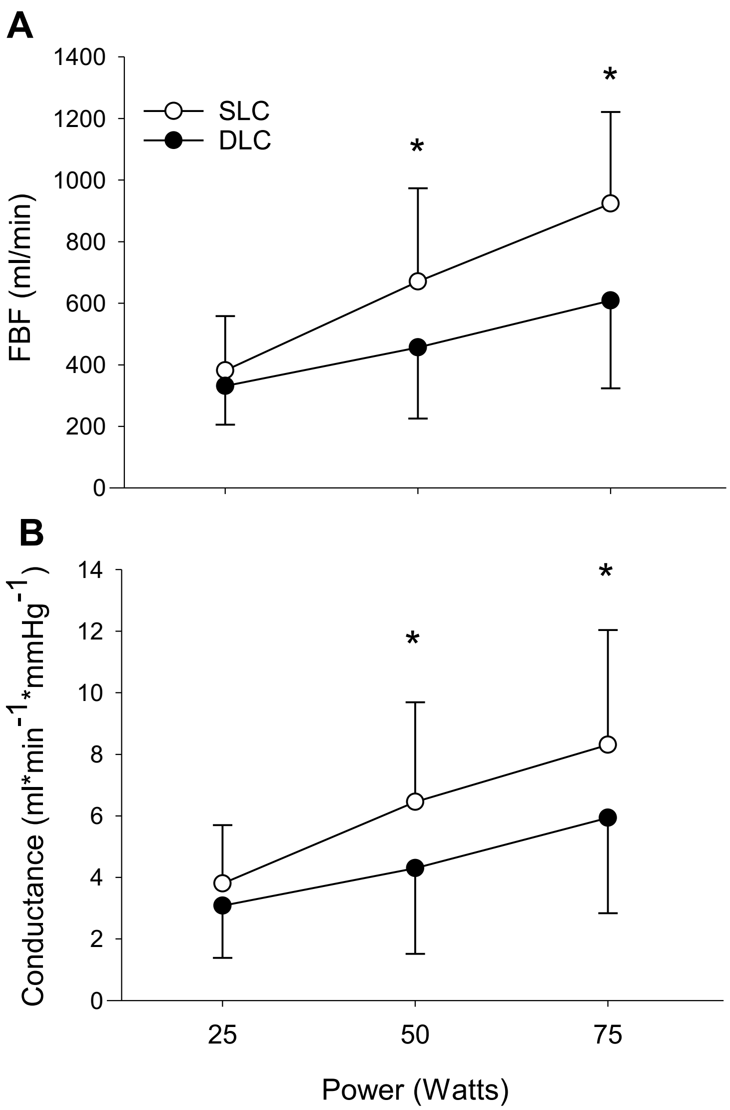

Figure 2. Femoral blood flow (FBF) and vascular conductance during single-leg (SLC) and double-leg cycling (DLC) across three work rates. There was a main effect of work rate for FBF and vascular conductance. * Indicates a significant difference between cycling modalities (p < 0.05).

Metabolic Responses: The repeated measures ANOVA revealed a main effect of cycling modality ($F=40.38$; $p<0.001$; ES=0.785) and work rate ($F=45.25$; $p<0.001$; ES=0.78) but not their interaction ($F=0.399$; $p=.676$) on RER. RER was significantly greater during SLC compared to DLC at all three exercise intensities ($p \leq 0.003$). Likewise, there was also a main effect of cycling modality ($F=22.37$; $p=0.001$; ES=0.52) and work rate ($F=79.06$; $p<0.001$; ES=0.88) as well as their interaction ($F=8.66$; $p=0.002$; ES=0.41) for carbohydrate oxidation. Carbohydrate oxidation was greater during SLC compared to DLC at 25 ($p=0.011$; ES=0.61), 50 ($p<0.001$; ES=0.57) and 75W ($p=0.003$; ES=0.98) (Figure 3B).

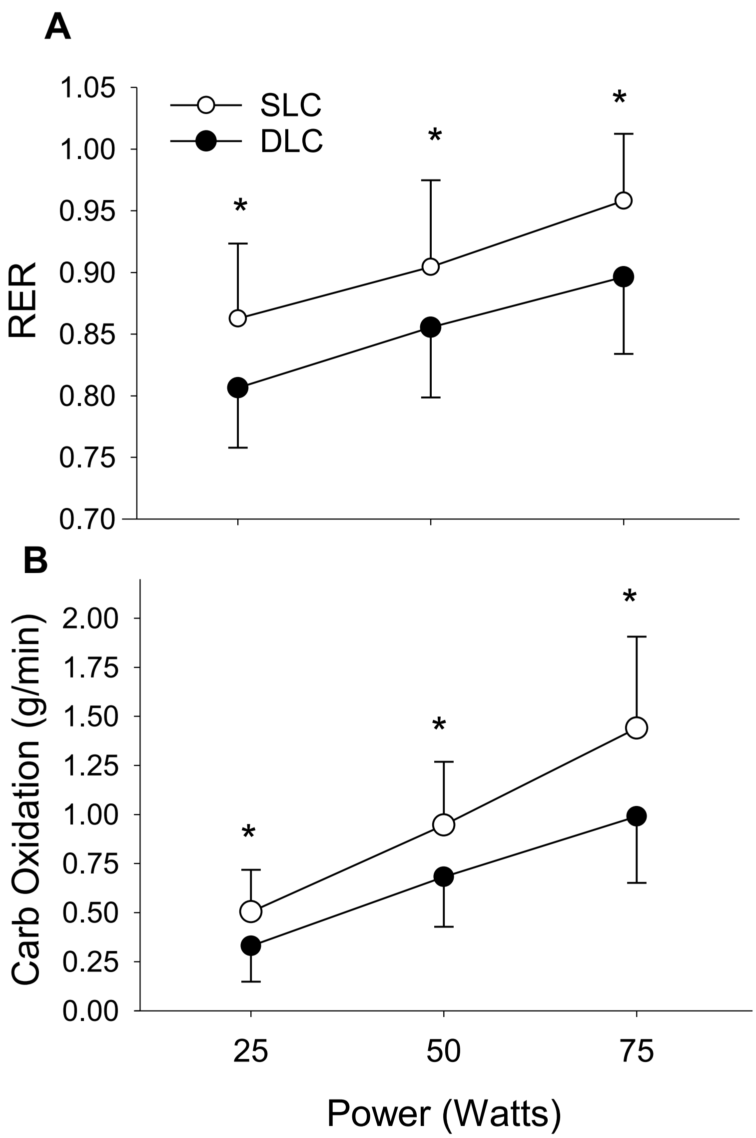

Figure 3. RER and carbohydrate oxidation during single-leg cycling (SLC) and double-leg cycling (DLC) cycling across three work rates. There was a main effect of work rate for RER and carbohydrate oxidation. * indicates a significant difference between cycling modalities ($p \leq 0.05$).

Perceptual Reponses: There was a main effect of cycling modality (F=6.47; p=0.029; ES=0.393) and work rate (F=29.93; p<0.001; ES=0.84) on total body RPE but not their interaction (F=2.94; p=0.104). Total body RPE for 25W and 50W was not different between DLC and SLC (p≥ 0.068), however, RPE at 75W was significantly greater in SLC (p= 0.042; ES = 0.69) (Figure 4A). Focusing in on the legs, the analysis also revealed a main effect of cycling modality (F=15.04; p=0.005; ES=0.653) and work rate (F=141.7; p<0.001; ES=0.947) on leg RPE but not their interaction (F=3.22; p=0.067) SLC Leg RPE were significantly higher than DLC for all work rates (25W p=0.011, ES=0.77; 50W p=0.014, ES=1.01; 75W p=0.018, ES=1.13) (Figure 4B). Liking scores were not significantly different between cycling modalities (p=0.065). Mean liking score was not different between the two conditions (7.47 ± 2.17cm for SLC and 7.95 ± 1.86cm DLC) indicating that participants had a moderate liking for both the exercise modalities (Figure 5).

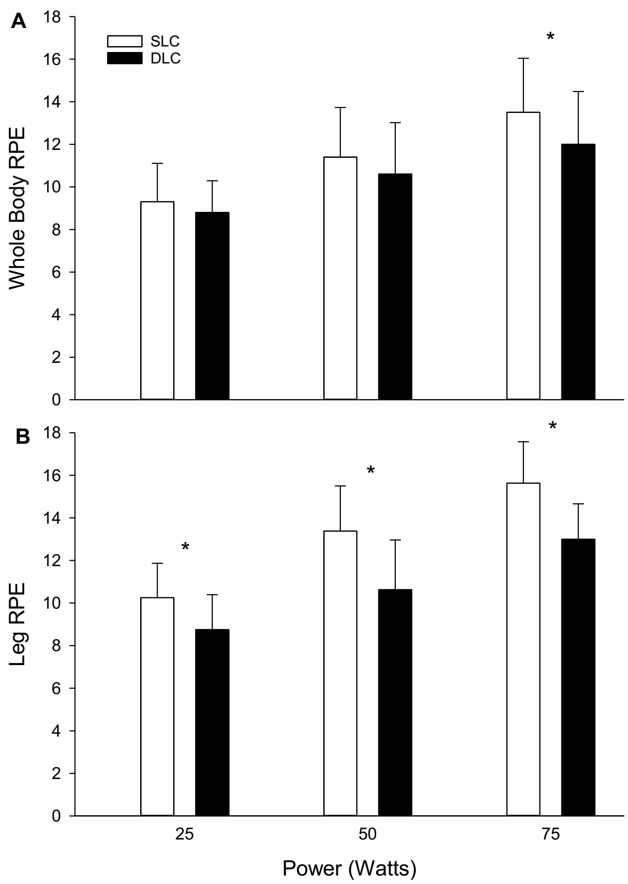

Figure 4. RPE for the whole body and legs during counterweighted single-leg (SLC) and double-leg (DLC) cycling across three work rates. There was a main effect of work rate for whole body RPE and leg RPE. * indicates a significant difference between cycling modalities (p≤0.05).

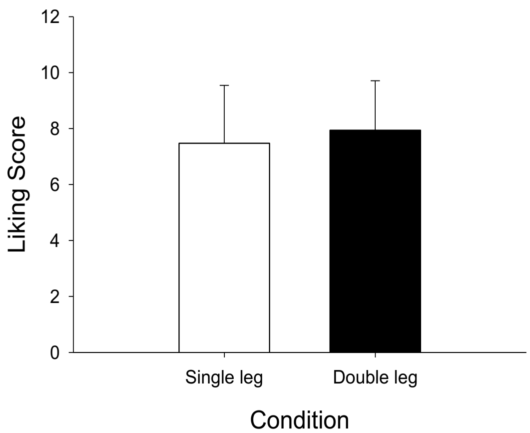

Figure 5. Liking score following double-leg and counterweighted single-leg cycling that included three work rates.

DISCUSSION

This investigation examined the cardiovascular and perceptual responses of traditional DLC to counterweighted SLC in a healthy older male population. The results from this investigation indicate that healthy older men tolerated and perceived SLC as well as DLC. Furthermore, the results from this investigation are similar to the results of previous investigations of DLC and SLC tested in a young healthy male population (5). SLC with a counterweight can double the work performed by the muscles of the lower limb and increase blood flow to that limb, while maintaining nearly similar cardiovascular response to normal DLC. These results have implications to exercise rehabilitation for the aging population as well as those with lower limb injury/amputation or diseases in which oxygen delivery is severely limited (COPD and heart failure) or maximizing hyperemia is beneficial (peripheral arterial disease).

Cardiovascular and Blood Flow Responses: Results of this study indicate that SLC with a counterweight produces cardiovascular responses that are similar to that of traditional DLC, while doubling the work performed by the lower limb. HR and MAP were not different between cycling modalities across all three work rates. Similarly, there was no significant difference in VO_2 between cycling modalities. During DLC, the three work rates utilized in this study (25, 50, and 75W) elicited approximately 26.6 ± 3.5%, 36.5 ± 4.0%, and 43.1 ±5.7% of estimated VO_2max while during SLC these work rates elicited approximately 25.3 ± 2.8%, 36.6 ± 4.4%, and 48.1 ± 8.2% of estimated VO_2max. Burns et. al. (2014) noted in the young male population, HR was significantly greater during SLC compared to DLC at the highest work rate (120 watts) but not at the lower work rates (40 and 80 watts). However, in the current study Both HR and MAP remained similar between SLC and DLC across all intensities. At lower intensities (25W and 50W) VO_2 remained nearly identical to that of DLC. At 75 watts, although not significantly different, VO_2 between the two modalities tended to separate and it is possible that at higher intensities beyond 75 watts VO_2 would be significantly different. It is likely that at higher intensities participants must recruit more stabilizing muscles in the core or upper body during SLC resulting in an increase in VO_2 beyond what is required for normal DLC.

Although HR, MAP and VO_2 were not different between modalities, FBF of the active limb was significantly greater during the SLC for 50 and 75W compared to DLC. Specifically, SLC resulted in a 31.4 ± 20.5% and 31.5 ± 15.1% greater FBF at 50W and 75W, respectively. Vascular conductance of the femoral artery was also greater at the 50W and 75W for SLC compared to DLC. Together, the similarities in HR and MAP between SLC and DLC and the greater vascular conductance with SLC suggests that the increase in FBF can be contributed to the greater metabolic demand of the working muscle which likely results in greater release of local metabolic and endothelium released vasodilators (nitric oxide/prostacyclin) (27,32). The increase in local blood flow during SLC is promising for clinical application in peripheral artery disease therapy, as the increase in shear stress could promote improvements in endothelial function (31) and angiogenesis (34). Furthermore, more recent evidence has implicated skeletal muscle dysfunction as a major contributor to exercise intolerance and poor quality of life in individuals with heart failure (8,17,19) SLC, which can maximize peripheral blood flow and limb specific work without excessive cardiovascular response can serve as an ideal exercise intervention for this population.

Metabolic Responses: In addition to the greater FBF across all intensities with SLC, substrate utilization also differed between the two cycling modalities. Specifically, RER and carbohydrate oxidation were significantly greater for SLC compared to DLC across all intensity levels suggesting greater carbohydrate utilization. This difference is expected based on the doubling of the leg-specific work rate. For example, during the 50W stage each leg would effectively contribute 25W. However, during the SLC modality all 50W was produced by the active leg resulting in greater glucose utilization and subsequently increased RER compared to normal DLC. There were several subjects that exceeded an RER of 1.0 (1.01-1.05) during SLC which makes the energy expenditure calculations invalid. For those individuals, carbohydrate utilization was calculated as if RER was at 1.0 and therefore likely underestimated their true carbohydrate oxidation during the SLC modality. The elevated RER during SLC agrees with Burns et al. (2014) who also reported greater RER values at 40, 80, and 120W during SLC compared to DLC for young healthy individuals (5). This could have implications for acute glucose control in diabetic patients, providing an aerobic exercise modality that has greater glucose oxidation, and therefore may help stabilize post prandial blood glucose compared to traditional exercise modalities. In fact, Abbiss et al. (2011) found that 6 weeks of SLC training increased GLUT-4 and AS160 content in elite cyclists who were already highly trained (1). Thus, SLC could likely improve long term glucose control in sedentary or minimally active populations.

Perceptual Responses: Previous reports indicate that SLC without a counterweight is poorly perceived as an exercise modality (5), while participants perceive SLC with a counterweight much better. This result is likely because SLC with a counterweight reduces the amount of work required during the upstroke phase of cycling, thus reducing the amount of work required by the fatigable hip flexor muscles during the exercise. In addition, the counterweight allows for a more fluid movement during cycling and produces more similar cycling biomechanics to that of DLC. Despite the similarity in biomechanics between the two modalities, there was a significant difference in RPE for both body and leg, however participants did not indicate a greater preference to either double or SLC. Specifically, liking scores were not significantly different between the two modalities. This suggests that SLC with a counterweight is well perceived and tolerated well among healthy older male subjects. Furthermore, liking score results suggest that participants are just as willing to perform SLC with a counterweight as DLC making SLC a possible exercise modality for older adults or diseased individuals.

Single-Leg Cycling: SLC with a counterweight reduces but does not eliminate the biomechanical differences between SLC and DLC (13) . Most notably, the muscular forces required to bring the leg back up to the top are much greater during SLC compared to traditional DLC. However, this difference is reduced by half with the use of a counterweight. This helps reduce the need to recruit hip flexors during the upstroke and improves the ability to coordinate the activity. With regards to the counterweight itself, the counterweight stores and releases potential energy within a single pedal cycle but does not increase or decrease energy over a complete cycle. In other words, energy delivered to the counterweight during the knee extension action (0-180 degrees) was returned from the counterweight during leg flexion (180-360 degrees). At the end of one pedal revolution, the height of the counterweight is the same. Thus, the use of the counterweight merely alters how the power is produced between muscle groups but does not contribute to total power production. SLC has also been successfully used in previous studies with COPD patients using a fixed gear cycle ergometer with much success (9,10). Fixed gear cycle ergometers, especially those with heavy flywheels, likely also facilitate natural cycling biomechanics for SLC as the inertial load of the flywheel assists the active leg on the upstroke similar to the counterweight in our model. It is likely that in a clinical population such as COPD and heart failure in which power produced by the subject is relatively low (25-75W single leg) and therefore resistance on the flywheel is also low, the kinetic energy of the spinning flywheel may be sufficient to assist with hip flexion with minimal deviation of angular velocity of the crank. Thus, SLC with a fixed gear ergometer is a great alternative to the counterweight for a clinical setting with patients that have a low exercise capacity (<75W). The pros and cons between fixed gear and counterweight SLC have been previously reported (4). However, if the mass of the flywheel is small or the power output is large (150W single leg), kinetic energy may be insufficient to assist with leg flexion without large scale changes in instantaneous crank angular velocity.

Limitations: The current study comes with some limitations that must be addressed. The sample size of participants is relatively small (n=11). The modality of counterweighted SLC requires a slight modification to the typical bike ergometer which includes replacing the pedal with a modified spindle that can hold traditional circular weights (note: this could be accomplished at any machine or metal shop). SLC also likely requires greater time commitment compared to DLC due to the necessity to exercise each leg independently.

In conclusion, results from this study indicate that SLC with the use of a counterweight will significantly increase FBF to the working limb (without an elevated cardiovascular response) when compared to traditional DLC. Additionally, participants in this study report no significant difference in liking scores, indicating that SLC with a counterweight can be easily implemented into an exercise program. Future studies should investigate the feasibility and possible training adaptations to counterweighted SLC in populations with limited either cardiac output and/or those that can benefit from greater hyperemic responses (ex: heart failure and peripheral arterial disease). The positive results from this study, suggest that SLC with a counterweight would be feasible to use in cardiovascular rehabilitation programs.

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