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Ground reaction forces and osteogenic index of the sport of cyclocross

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Abstract

Weight-bearing activity has been shown to increase bone mineral density. Our purpose was to measure vertical ground reaction forces (GRFs) during cyclocross-specific activities and compute their osteogenic index (OI). Twenty-five healthy cyclocross athletes participated. GRF was measured using pressure-sensitive insoles during seated and standing cycling and four cyclocross-specific activities: barrier flat, barrier uphill, uphill run-up, downhill run-up. Peak and mean GRF values, according to bodyweight, were determined for each activity. OI was computed using peak GRF and number of loading cycles. GRF and OI were compared across activities using repeated-measures ANOVA. Number of loading cycles per activity was 6(1) for barrier flat, 8(1) barrier uphill, 7(1) uphill run-up, 12(3) downhill run-up. All activities had significantly ($P < 0.01$) higher peak GRF, mean GRF values and OI when compared to both seated and standing cycling. The barrier flat condition ($P < 0.01$) had highest peak (2.9 times bodyweight) and mean GRF values (2.3 times bodyweight). Downhill run-up ($P < 0.01$) had the highest OI (6.5). GRF generated during the barrier flat activity is similar in magnitude to reported GRFs during running and hopping. Because cyclocross involves weight bearing components, it may be more beneficial to bone health than seated road cycling.

Keywords

physical activity; bone health; osteogenic; cycling; loading cycles

Introduction

Extensive research has been conducted regarding the potential benefit of exercise on bone health. Current recommendations are that persons of all ages engage in weight-bearing activity and resistance training to maximise accrual of bone mineral density and attenuate its age-related losses (Kohrt, Bloomfield, Little, Nelson, & Yingling, 2004). However, an individual's choice of exercise modality greatly influences the amount of weight-bearing.

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This is important as bone mineral density optimisation through impact activity may reduce the risk of osteoporosis and fragility fractures (Guadalupe-Grau, Fuentes, Guerra, & Calbet, 2009).

During weight-bearing exercise, external gravitational loads (ground reaction forces, GRFs) are attenuated by bone and surrounding soft tissue (Kohrt, Barry, & Schwartz, 2009). The impact from weight-bearing activities may stimulate both bone modelling and remodelling, and the osteogenic capacity of a particular exercise is dependent on multiple characteristics of the applied strain (duration, frequency and intensity) (Barry & Kohrt, 2008). Although the optimal exercise programme for bone health is unknown, mechanical loading experienced irregularly and at high-strain rates and magnitudes appears to improve bone mineral density to a greater degree than repetitive, lower-impact or non-weight-bearing exercises (Barry & Kohrt, 2008; Manske, Lorincz, & Zernicke, 2009). Furthermore, loading cycles optimal for osteogenesis are separated by substantial bouts of rest, a phenomenon stemming from a bone's intrinsic mechanical desensitisation and remodelling to withstand prolonged stimuli (Robling, Burr, & Turner, 2001; Rubin & Lanyon, 1984; Turner & Robling, 2003). In order to quantify the osteogenic efficacy of an exercise regimen, Turner and Robling developed a measure known as the osteogenic index (OI), which estimates bone formation based on peak GRF value (a surrogate measure of bone strain intensity) and the number of loading cycles applied, addressing the degree of osteodesensitisation (Turner & Robling, 2003). Weight-bearing exercise that involves intermittent, high-magnitude impacts may provide the most beneficial stimulus for bone formation.

Cross-sectional studies evaluating bone mineral density using dual-energy X-ray absorptiometry have revealed significantly higher bone mineral density in weight-bearing sport athletes, such as gymnasts or runners, compared to cyclists or swimmers (Andreoli et al., 2001; Duncan et al., 2002; Maimoun et al., 2004; Morel, Combe, Francisco, & Bernard, 2001; Rector, Rogers, Ruebel, & Hinton, 2008; Stewart & Hannan, 2000; Taaffe, Robinson, Snow, & Marcus, 1997). The positive correlation between weight-bearing activities and bone mineral density may be partly attributable to mechanical stress imparted on the skeleton during ground impacts absent in non-weight-bearing sports (Kohrt et al., 2004). There is evidence that endurance athletes such as road cyclists exhibit significantly lower bone mineral density in the spine and hip compared to non-athletes; therefore there is concern that the biomechanics of road cycling may not adequately stimulate bone formation (Burnfield, Jorde, Augustin, Augustin, & Bashford, 2007; Nichols, Palmer, & Levy, 2003; Nichols & Rauh, 2011; Stewart & Hannan, 2000). Warner et al.'s study comparing competitive male mountain bikers and road cyclists revealed significantly higher bone mineral density in mountain bikers (Warner, Shaw, & Dalsky, 2002). The distinct difference between road cycling and mountain biking is that the latter requires more standing and shifting of one's body weight on the pedals, in addition to the rider experiencing larger external forces at the foot due to the varied terrain involved (De Lorenzo & Hull, 1999).

Cyclocross is an emerging competitive sport described as a hybrid between mountain biking and road cycling. Cyclocross is similar to mountain biking in terms of terrain (pavement, wooded trails, grass, steep hills, and obstacles), but, in addition, requires the rider to perform weight-bearing activity. Specifically, the rider is required to repeatedly dismount, carry or

push the bike while running and jumping over an obstacle and/or uphill, and then remount; this is unique to cyclocross as mountain bikers often are able to ride over barriers they encounter. To our knowledge, the GRF and osteogenic potential of cyclocross have not been examined. It is plausible that the high-intensity loading cycles followed by periods of seated or standing cycling, unique to cyclocross, may have a larger osteogenic effect on bone compared to repetitive lower-intensity activities without periods of relative rest. The objectives of this study were to measure peak and mean vertical GRF values during cyclocross-specific activities and calculate their OI. We hypothesised that the peak GRF value and OI would be greater for all cyclocross activities when compared to seated and standing cycling. As a sport, we hypothesised that the OI of cyclocross participation would be greater than other repetitive activities, given the incorporated periods of cyclocross-specific weight-bearing activities.

Methods

Participants

Twenty-five participants participated in this study. Participants were included if they were over 17 years of age and had participated in cyclocross for a minimum of 1 year. Participants were excluded if they (a) had sustained a musculoskeletal injury requiring medical attention and cessation of physical activity within 4 weeks of study enrollment and (b) had known neurologic or orthopaedic conditions that would interfere with exercise. The study was approved by the University of Wisconsin-Madison Institutional Review Board. Each participant gave written informed consent prior to participation.

Procedures

All participants completed a self-report questionnaire to collect age, self-reported height, dominant leg/arm, current level and years of cyclocross experience, and number of hours per week and months per year participating in cyclocross activity. Body mass index (BMI) was calculated using the self-reported height and a body weight measured on an electronic scale the day of data collection (Taylor Precision Products, Oak Brook, IL).

Pressure-sensitive insoles (Novel Electronics Inc., Munich, Germany) were used to collect plantar foot pressure data during cyclocross-specific activities. Each pressure insole consists of a 2-mm thick array of 99 capacitive pressure sensors which were sampled at a rate of 100 Hz. Each participant was fitted with the appropriately sized insole. Cyclists used their own shoes and cyclocross-specific bike; mountain bikes or road bikes were not permitted. Bike weight was not recorded. A Garmin Edge 800 GPS unit (Garmin International Inc., Olathe, KS, USA) was attached to each participant's bike to record speed (kmph) and per cent grade of each trial. Obstacles for dismount/remount activities were barriers constructed using lightweight plastic PVC pipe in accordance with UCI cyclocross standards: 40 cm high and placed 4 m apart.

All testing was performed on grassy surfaces at Garner Park in Madison, WI, which served as the site of organised practices for Madison area cyclocross riders. The pressure-sensitive insoles were placed between each participant's shoe insole and sock before their shoes were

fastened and then zeroed according to the manufacturer's guidelines. Participants were allowed to warm up for 10 min prior to data collection.

Each participant performed a seated cycling trial at an easy-to-moderate pace in addition to a maximal-effort standing sprint trial for approximately 5–10 s. Then participants performed three sets of four cyclocross-specific activities at a self-selected speed: (a) *barrier flat* – dismount on flat ground, jump over 2 barriers, remount; (b) *barrier uphill* – dismount on uphill, jump over 2 barriers, remount (11% grade); (c) *uphill run-up* – dismount on uphill, run uphill, remount (13% grade); (d) *downhill run-up* – dismount on downhill, 180 degree turn, run uphill, remount (13% grade). The four activities were each completed within 8–10 meters and 2.7–12.4 s. The cyclocross activities were randomly ordered for each participant to avoid fatigue bias affecting performance. Each trial was recorded with a Flip Video™ Ultra HD digital camera (Cisco, San Jose, CA, USA).

Data analysis

Loading cycles were determined from for each insole and cyclocross-specific activity. A loading cycle was determined as either: (a) time the foot was in contact with the ground until the subsequent contact on same foot (running and jumping) or (b) when measured forces reached a peak during pedalling until subsequent peak force (seated or sprint cycling). Separate loading cycles were then determined for each foot and averaged.

Three trials were collected for each activity as the distance between the moving participant and laptop computer affected the quality of wireless data transmission. Each trial was visually inspected, and the one exhibiting the most consistent trace was selected for analysis. To determine GRF for an activity trial, the pressure reading from each insole was multiplied by the respective area of each sensor. These numbers were then summed to yield the GRF trace versus time. Dismount and remount loading cycles were determined from the insole data using a customised MATLAB routine (Mathworks, Inc. Natick, MA, USA). During dismount, a relatively constant GRF is seen as each participant balances on the left pedal while swinging the right leg around to the left side of the bike (Figure 1 – photo). For example, in the barrier flat condition, the first peak represents initial ground contact during bicycle dismount when the right foot strikes ground. The left foot is simultaneously unclipped from its pedal and strikes ground before the bike is lifted over the barriers. The force peaks immediately following the dismount represent a series of jumps and landings over two barriers. Depending on the cyclist's efficiency, a variable number of steps were taken before, between, or after the barriers prior to remount resulting in a variable number of loading cycles for each participant. After jumping over the second barrier, the participant remounts the bicycle by pushing off the ground with the left foot, jumping onto the bike seat, clipping into the pedals, and pedalling once again. Remount was determined when each participant resumed a rhythmical, sinusoidal pedalling pattern (Figure 2 – trace figure for right and left legs).

Outcome measures

Vertical GRFs were analysed during pedalling in seated and sprinting trials and during cyclocross-specific activities every time each foot struck the ground while running, jumping

or landing. The GRF with the largest magnitude constituted the peak GRF; this value and the loading cycle in which it occurred was then determined for each of the four cyclocross activities. Additionally, using the FlipVideo™ digital recording, we determined where, throughout each trial peak, GRF loading cycles occurred in order to determine if one particular impact (e.g. foot strike at dismount or landing from a barrier jump) consistently yielded the greatest forces. Mean GRF value was calculated for each activity to represent average force of all loading cycles experienced between dismount and remount. For each participant, peak GRF and mean GRF values were normalised to body weight [reported as GRF by bodyweight, e.g. 1.9 bodyweight]. In addition, an average loading rate ($\text{N} \cdot (\text{kg} \cdot \text{s})^{-1}$) was determined for each loading cycle; this was computed as the average slope of the ground reaction curve between the time points corresponding to 20% and 80% of the peak force for the specific loading cycle. The OI defined by Turner and Robling was calculated for each cyclocross activity (Turner & Robling, 2003):

$$OI(activity) = vGRF \times \ln(LC + 1) \quad (1)$$

where $vGRF$ is the peak GRF and LC is the number of loading cycles.

Statistics

Descriptive statistics (means and s) were calculated for demographic, anthropometric, GRF by bodyweight and OI variables. Pearson product moment correlation coefficient was used to assess strength of association between peak GRF by bodyweight, and cycling speed (km/h) generated during cyclocross specific activities. One-way repeated measures ANOVA was used to compare loading cycles, peak GRF by bodyweight, mean GRF by bodyweight, and OI between all activities (cyclocross activities and cycling activities), with significant main effects evaluated using Tukey's honestly significant difference, which adjusts for multiple comparisons.

Results

Twenty-five cyclocross athletes participated (18 males, 7 females). Mean age was 35.5 (8.3) years with mean body weight 73.3 (10.2) kg and BMI 23.1 (2.3) $\text{kg} \cdot \text{m}^{-2}$. Athletes reported 3.8 (2.5) years of competitive cyclocross experience and average cyclocross-specific training of 4.4 (2.8) hours per week and 3.6 (0.7) months per year. All but one participant indicated both right leg/arm dominance, and all dismounted on the left side of the bicycle. Except for two, all participants regularly participated in at least one other form of cycling including road, time trial, mountain biking, and/or triathlon.

Cycling speeds, number of loading cycles, GRF normalised to bodyweight, loading rate and OI of seated pedalling, standing pedalling and cyclocross-specific activities are shown in Table I. Number of loading cycles varied significantly ($P < 0.01$) between all four activities with downhill run-up resulting in greatest number of cycles and barrier flat, the least. On average, a trial of each cyclocross-specific activity took less than 10 s to complete. Downhill run-up had the longest duration (6.9 ± 1.7 s) and barrier flat had the shortest duration (3.6 ± 0.6 s). All four cyclocross activities had a significantly ($P < 0.01$) greater peak GRF by bodyweight, than the seated cycling or standing sprint activity. Additionally, mean GRF by

bodyweight, for each activity, was significantly higher ($P < 0.01$) than for seated or standing sprint cycling. The barrier flat condition showed the significantly ($P < 0.01$) highest peak and mean GRF by bodyweight, while the uphill run-up activity had the lowest ($P < 0.01$). Loading rate was greatest for the barrier flat condition ($62.6 \pm 15.8 \text{ N} \cdot (\text{kg} \cdot \text{s})^{-1}$, $P < 0.01$) and similar across the other three cyclocross activities ($39.1\text{--}44.4 \text{ N} \cdot (\text{kg} \cdot \text{s})^{-1}$, Table I).

The individual loading cycle exhibiting the largest magnitude peak GRF by bodyweight was variable between cyclocross-specific activities. For the conditions involving barriers (barrier flat and barrier uphill), peak GRF by bodyweight occurred most often during jumping push-off or landing foot strikes. Conversely, for uphill and downhill run-up conditions with no barriers, peak GRF by bodyweight was predominantly seen at initial foot strike during bicycle dismount rather than the following loading cycles as participants ran with their bikes down- and/or up-pitched terrain. The OI calculated for the four cyclocross conditions was significantly ($P < 0.01$) greater than the OI calculated for seated and standing sprint cycling. Of the four movements, downhill run-up sequence had the ($P < 0.01$) highest OI and uphill run-up had the lowest OI.

The barrier uphill condition showed the fastest average and maximum cycling speeds of the four activities, while downhill run-up showed both the slowest average and maximum speeds (Table I). The average and maximum cycling speeds achieved during cyclocross-specific activities were not correlated with mean GRF by bodyweight in all cases except for barrier uphill; for this activity, maximum cycling speed had a positive correlation with mean GRF by bodyweight ($r = 0.65$, $P < 0.01$), as cyclists picked up maximum speed on flat ground before ascending to the barriers.

Discussion

Our study measured the GRF normalised to body weight and OI of unique, weight-bearing cyclocross activities and demonstrated that they are significantly greater than those of seated and standing sprint cycling. Of these conditions, barrier flat activity showed the highest mean and peak GRF by bodyweight with maximum forces generated most often during jumping or landing. The downhill run-up sequence demanded the greatest number of loading cycles, and also yielded the largest OI calculation. While there are obvious cardiovascular and metabolic health benefits associated with exercise, research has shown that bone mineral density of endurance athletes may be jeopardised due to lack of weight-bearing activity (Duncan et al., 2002; Nichols et al., 2003; Rector et al., 2008; Stewart & Hannan, 2000). In contrast to road cycling, cyclocross incorporates bouts of running and jumping while pushing or carrying a bicycle, in addition to pedalling on uneven terrain; these activities may induce external gravitational loads that benefit skeletal health.

GRF values have been used as a surrogate measure of external gravitational loading experienced during various activities. Normalisation of peak GRF by bodyweight according to participant body weight (expressed as multiples of bodyweight) is common and allows for comparison across sports involving impacts (e.g. road cycling 0.8 bodyweight, walking 1.2 bodyweight, jump squat 3.8 bodyweight, basketball 4.7 bodyweight, gymnastics 10.0 bodyweight) (Weeks & Beck, 2008). Additionally, normalisation to body weight alone

makes our results comparable across studies. High skeletal loading magnitude has been defined as GRF value of greater than four times body weight, and low skeletal loading magnitude as less than two times body weight (Santos-Rocha, Oliveira, & Veloso, 2006). The peak GRF associated with the barrier flat activity (2.9 bodyweight) is similar to running (2.6 bodyweight) and soccer (2.4 bodyweight) (Figure 3) (Groothausen, Siemer, Kemper, Twisk, & Welten, 1997; Weeks & Beck, 2008). The similarity seen between the barrier flat condition and soccer is not surprising, considering the similar grassy terrain on which running and jumping occurs.

The peak GRF during the barrier flat condition (2.9 bodyweight) is similar to that described for single-leg hopping on a force platform (3.4 bodyweight) (Weeks & Beck, 2008). Bailey and Brooke-Wavell demonstrated that 10 consecutive unilateral hops in premenopausal women generated mean peak GRF ranging from 2.4 to 2.6 bodyweight, and they concluded that a daily regimen of 50 unilateral hops significantly increased bone mineral density in the femoral neck of participants over a 6-month period (Bailey & Brooke-Wavell, 2010). Traversing barriers in the sport of cyclocross is certainly similar to the act of hopping, with respect weight-bearing magnitude. However, we did not measure bone mineral density in this study and do not know if regular practice and competition throughout a cyclocross season may benefit an athlete's bone mass to a degree similar to that described by Bailey and Brooke-Wavell. A simple hopping intervention might also be a very beneficial, easy-to-perform strategy for strict road cyclists to help maintain their bone health.

The forces applied at the foot while pedalling have been previously described. Soden and Adeyefa concluded that an outdoor road cyclist traveling at a speed of $37 \text{ km} \cdot \text{hour}^{-1}$ applies approximately 50% of his body weight to the pedals. In instances where a rider climbs a 10% incline, push force to the pedals can slightly exceed body weight (Soden & Adeyefa, 1979). The peak (0.6 bodyweight) and mean GRF (0.5 bodyweight) values, reported in the present study for a typical loading cycle during seated pedalling, fall at the lower end of the range previously reported, though participants were simply instructed to ride at a comfortable slower pace, likely contributing to the lower value. (Soden & Adeyefa, 1979; Weeks & Beck, 2008)

Conversely, the peak and mean GRF values measured for the standing sprint cycling trials were 1.6 bodyweight and 1.4 bodyweight, respectively. These values, not surprisingly, both exceed the range cited for non-incline road cycling as each loading cycle was measured while participants exerted maximal effort on the pedal on a grassy surface, which is presumably more difficult than achieving top speeds on a smooth pavement (Soden & Adeyefa, 1979; Weeks & Beck, 2008). These higher forces better reflect the demands of cyclocross as they relate to off-road cycling. Cyclocross is similar to mountain biking, in that both sports require athletes to frequently accelerate and decelerate as they avoid obstacles, make sharp turns and traverse bumpy terrain. During a typical cyclocross event, standing on the pedals is often needed to gain speed, coast downhill or "bunny-hop" unpredictable obstacles; balancing on one pedal during the bicycle dismount is a skill unique to this sport, and it demands increased weight-bearing. Compared to seated road cycling, for example, less than half of a rider's weight may be transmitted to the pedals, while as much as 70–90% of a mountain biker's body weight may be applied on the pedals while standing

and coasting or traveling downhill (Rowe, Hull, & Wang, 1998; Wang & Hull, 1997). Obstacles and bumpy trails yield unpredictable forces that are absorbed through the legs while an off-road cyclist stands on the pedals (Wang & Hull, 1997). The off-road nature of cyclocross, in addition to the frequent bouts of weight-bearing activity, may therefore provide osteogenic stimuli not inherent to road cycling.

OI calculations were performed to gauge how the bone forming potential of cyclocross conditions compare to each other, as well as to other impact-specific movements. The downhill run-up had the highest OI (6.5). While this condition did not exhibit the highest peak or mean GRF value (2.5, 1.9 bodyweight), it did require the greatest number of loading cycles on average (11.9) (Table I). This point illustrates the effect of loading cycle quantity on the OI during the brief weight-bearing spurts seen in cyclocross. Importantly, the body's osteogenic response to weight-bearing activity saturates quickly; this phenomenon is well supported by numerous animal models that highlight the importance of rest between periods of intense mechanical loading, permitting re-sensitisation of bone to future strains (Robling, Burr, & Turner, 2000; Rubin & Lanyon, 1984; Turner & Robling, 2003). Cyclocross follows this pattern of higher-intensity loading cycles separated by periods of relative rest; the four weight-bearing activities evaluated in the present study are interspersed by more sustained periods of seated and standing pedalling during a typical cyclocross race or practice. The cyclic variation in intensity of GRF imparted on the body during cyclocross may be more beneficial in terms of osteogenesis than other repetitive, lower-intensity weight-bearing activities not separated by periods of relative rest.

The OI has been used as a comparative measure of bone-forming potential of weight-bearing movements. For example, the OI of performing 120 jumps in one session (3.0 bodyweight, 120 loading cycles) is 14.4, and the OI for a 20 min walk (1.1 bodyweight, 800 loading cycles) is 7.4 (Turner & Robling, 2003). Santos-Rocha et al. found the OI of an aerobic step exercise class of approximately 40 min duration to be 12.0 (Santos-Rocha et al., 2006). Other studies have correlated the OI of various activities with certain markers of bone response (Erickson & Vukovich, 2010; Lester et al., 2009). Erickson and Vukovich found a significant increase in bone alkaline phosphatase, a marker of bone formation, in a cohort of participants who completed a 8-week regimen of two jumping sessions/day with a higher OI than those performing only one jumping session/day (Erickson & Vukovich, 2010). Daly and Bass utilised the OI to temporally quantify the lifetime participation of participants in various weight-bearing activities (Daly & Bass, 2006). Higher OI values positively correlated with greater bone size, strength and quality at loaded sites, according to quantitative computed tomography. Interestingly, the time spent participating in weight-bearing activity did not accurately predict this better bone structure, supporting the relative importance of peak strain intensity on bone adaptation compared to duration performed. Despite the correlations drawn from the aforementioned studies, we acknowledge that the OI has not been validated, and the OI value optimal for bone growth remains unknown. Numerous studies, including the present, have retrospectively measured the OI of various activities. However, to our knowledge, no longitudinal research has prospectively evaluated bone mineral density or osteogenic biomarkers in response to exercise regimens of predetermined OI.

Figure 4 visually depicts the OI of cyclocross activities in the context of other weight-bearing activities performed at varying intensities and loading cycles. It is important to note that the landing terrain can be variable, such as grass, concrete, mud or hard-packed dirt. Also, type and frequency of cyclocross activities can be variable, depending on how courses are designed and the amount of time an individual practices or competes. Using the method described by Santos-Rocha, we calculated the OI of a cyclocross race that takes 60 min and requires the cyclist on a grass surface to perform 10 uphill run-ups with no barriers and to jump over two sets of barriers 10 times on flat terrain, in addition to 10 min of standing sprint pedalling (120 rpm, 1.6 bodyweight) and 40 min of seated cycling (90 rpm, 0.6 bodyweight). Santos-Rocha et al. employed this method to determine loading intensity during various aerobic step exercise programmes that incorporate multiple movements by calculating peak GRF as a weighted average based on the fraction of total loading cycles completed at a particular intensity (Santos-Rocha et al., 2006). This is an alteration of the original OI calculation as defined by Turner and Robling. (Turner & Robling, 2003) The remaining calculations presented in Figure 4 utilise the OI calculation as originally described for activities completed all in one session, like those done in the present study, to provide a more comparative value. As discussed above, rest insertion is thought to enhance bone-forming potential of a particular exercise; this phenomenon was not explicitly tested in the present study, but could be an area of further investigation.

The study limitations point to avenues of future research. The current insole system only measures vertical GRFs. Despite the OI calculation only accounting for the forces vertically transmitted through bone, it is possible that shear forces play an important role in loading the skeleton. The OI does not include a measure of individual bone density, mass or size, which do influence bone strain stimulus; therefore, its suitability for assessing loading between different individuals is unknown. Bike weight was not included in the normalisation of GRF; however, not all cyclocross activities require the bike to be lifted and carried (e.g. pushing the bike uphill). Though not explicitly controlled for in the present study, other variables that could affect the number of loading cycles, and thus the OI, for each activity, include the self-selected participant's effort and speed at which the subjects approached the barriers, as well as the length of each activity. Many studies considering the osteogenic potential of mechanical loading specifically examine the rate of strain application. Strain rate appears to play an important role in the bone's osteogenic response, and higher strain rates in activities such as jumping appear to be most beneficial (Manske et al., 2009). The loading rates found for the barrier flat activity are comparable to the average loading rate for running at slow speeds, suggesting that the intermittent cyclocross activities may provide a beneficial stimulus to bone (Kluitenberg, Bredeweg, Zijlstra, Zijlstra, & Buist, 2012).

The goal of this study was to directly measure the GRF and estimate the osteogenic potential of cyclocross activities, but it did not directly measure bone mineral density or serum markers of bone turnover. Future research may expand on the data obtained in this study and follow a cohort of cyclocross athletes over a season to correlate the measured GRF with bone health by comparing their bone mineral density and measures of bone structure to other cyclists who do not participate in cyclocross. Additionally, only recreational and intermediate-level athletes participated in this study; therefore, it is possible that the external

loads generated may differ in more competitive professionals who are able to jump over barriers with better skill and higher speeds and who may utilise the momentum and weight of their bike to decrease the forces needed to dismount, lift the bike, jump and remount. In addition, we only investigated specific components of a cyclocross race, and it is possible that this loading may change when activities are combined. Lastly, we did not examine the relationship between pedalling cadence (e.g. 90 rpm), workload (watts) and the force applied directly to the pedal during the cyclocross activities, nor did we investigate potential gender differences, as our subject population was primarily male, which are all considerations for future research.

Conclusion

The sport of cyclocross provides athletes with brief bouts of weight-bearing activity that generate GRF similar in magnitude to running and hopping. We found that the barrier flat condition showed the largest peak and mean GRF values, and the OI of cyclocross movements is higher than seated and standing sprint cycling for an equivalent number of loading cycles. Because cyclocross involves more intense weight-bearing components interspersed with periods of relative rest, it may be more beneficial to bone health than seated road cycling. Participation in this sport is similar to other weight-bearing regimens and may help maintain or increase bone mass.

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Figure 1. Cyclocross racer completing a barrier flat activity, which involves dismounting on flat ground, jumping over two barriers, then remounting the bike.

Figure 2.

Graphical depiction of loading cycles and accompanying forces generated during a representative barrier flat trial. The relatively stationary force indicates the time when the rider is preparing for dismount, followed by a distinctive absence of force prior to the first impact as the rider dismounts the bicycle. The rider then performs a series of loading cycles followed by remounting and resumption of seated cycling.

Figure 3.

A comparison of peak vertical GRF values for seated cycling, standing sprint cycling and cyclocross-specific activities with data from literature-derived values.

Note: ★ From Groothausen et al. (1997) and Weeks and Beck (2008).

Figure 4.

A comparison of the calculated OI of cyclocross activities with the calculated OI of other repetitive and weight-bearing activities.

Notes: ¹120 rpm, GRF 1.6 BW.

²15 barrier flat activities.

³Lower extremity exercises, 3 sets of 3–12 reps against variable resistance, Lester et al. (2009).

⁴90 rpm, GRF 0.8 BW, Weeks and Beck (2008).

⁵80 steps/min (40 per leg), GRF 1.1 BW, Turner and Robling (2003).

⁶2 sets of 10 jumps against 80% BW resistance, Erickson and Vukovich (2010).

⁷Bailey and Brooke-Wavell (2008).

⁸Santos-Rocha et al. (2006).

⁹Against body weight only, GRF 3 BW, Turner and Robling (2003).

¹⁰160 steps/min (80 per leg), GRF 2.6 BW, Weeks and Beck (2008).

Table 1

Mean and standard deviation of cycling speed, number of loading cycles, peak and mean vertical ground reaction force (vGRF) normalised to body weight (BW), loading rate (slope of vGRF curve between 20% and 80% of peak vGRF) and OI of seated and standing sprint pedalling and cyclocross-specific activities.

Activities	Average speed (km · h ⁻¹)	Maximum speed (km · h ⁻¹)	Loading cycles (#)	Peak vGRF (BW)	Mean vGRF (BW)	Loading rate (N · kg ⁻¹ s ⁻¹)	Osteogenic index
Seated	14.2 (3.4)	19.3 (4.7)	4.2 (1.3)	0.6 (0.2)	0.5 (0.1)	N/A	1.0 (0.5)
Standing sprint	14.8 (3.4)	29.8 (6.1)	5.0 (1.2)	1.6 (0.3)	1.4 (0.3)	N/A	2.8 (0.5)
Barrier flat	12.6 (2.3)	21.6 (3.2)	6.0 (1.2)★	2.9 (0.4)★	2.3 (0.3)★	62.6 (15.8)	5.7 (0.9)★
Barrier uphill	13.4 (2.9)	23.8 (4.2)	8.5 (1.0)★	2.4 (0.3)★	2.0 (0.3)★	39.9 (14.6)	5.3 (0.8)★
Downhill run-up	9.0 (1.8)	15.4 (3.1)	11.9 (2.6)★	2.5 (0.4)★	1.9 (0.2)★	44.4 (10.1)	6.5 (1.1)★
Uphill run-up	11.7 (2.4)	20.6 (3.4)	7.1 (1.3)★	2.2 (0.4)★	1.9 (0.3)★	39.1 (12.3)	4.7 (0.8)★

Notes: BW is body weight; vGRF is vertical ground reaction force; km · h⁻¹ is kilometers per hour.

★ANOVA, $P < 0.01$, comparison to seated and standing sprint cycling.

Effect sizes: OI = 0.837, Peak vGRF = 0.820, Mean vGRF = 0.860, Loading cycles = 0.73.