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Abstract

Ahn, N, Kim, H, Krzyszkowski, J, Roche, S, and Kipp, K. Influence of the bar position on joint-level biomechanics during isometric pulling exercises. *J Strength Cond Res* 35(6): 1484–1490, 2021—The purpose of this study was to investigate the influence of the bar position on ankle, knee, and hip net joint moments (NJMs), relative muscular effort (RME), and vertical ground reaction forces (GRFs) during isometric pulling exercises, such as the isometric midthigh pull. Eight female lacrosse athletes performed maximal effort isometric pulls at 3 different bar positions (low: above patella, mid: midthigh, and high: crease of hip) while motion capture and GRF data were recorded. Net joint moments were calculated with inverse dynamics. Relative muscle effort was defined as the ratio between the inverse dynamics NJMs and the maximum theoretical NJMs, which were estimated with regression-based maximum moment-angle models. Peak NJM and RME were compared with 2-way analyses of variance (ANOVA), whereas GRFS were compared with a 1-way ANOVA. Peak vertical GRF were significantly greater in the mid bar position than the high bar position but did not differ between the low and mid bar position. Bar position significantly influenced peak hip and knee NJM and RME. Hip NJM and RME were greatest in the low bar position, whereas knee NJM and RME were greater in the mid bar position. Because hip and knee extensor NJM and RME differed between the low and mid bar positions, but the GRFS did not, the joint-specific contributions to peak isometric pulling forces likely reflected a trade-off between hip dominance and knee dominance in the low and mid bar position, respectively. This information should be considered in the interpretation isometric pulling data and their use in assessing and monitoring maximal force-producing capacity of the lower body.

Introduction

Isometric pulling exercises, such as the midthigh pull (IMTP), are multijoint isometric exercises that are used to provide information about an athlete's maximum and rapid force generating capacity ([5,8,9,13,19,28]). For example, IMTP performance is typically quantified with variables that are extracted from ground reaction force (GRF) data, such as peak force, rate of force development, and impulse. Importantly, these variables strongly correlate with dynamic performance during tasks such as weightlifting, cycling, and sprinting ([3,15,28,29]). Based on these characteristics, the IMTP provides a simple tool to assess lower-body muscle strength, prescribe training interventions, and monitor training adaptations ([4,10,11,15]).

Strength coaches and researchers have used various postures and bar positions during isometric pull testing ([5]). The IMTP, for example, is often performed with the body positioned in a posture that matches the second pull of the clean and with the bar located between the athlete's knee and hip joints ([5]). More specifically, initial research by Haff et al. ([18]) tested maximum force production of elite weightlifters during the IMTP by selecting knee and hip angles that matched the second pull position of the clean. Since then, other authors found that a body position with knee angles between 130° and 145° and hip angles around 145° enabled athletes to produce greater GRFs compared with other positions ([14,19,23,26,27]). Other studies also subsequently showed that changing body posture, joint angles, and bar position affects GRFs during the IMTP ([4,17]). Practical recommendations in the literature for the implementation of the IMTP are based partially on the findings of these studies, which in turn are the result of investigating GRF-based parameters.

Evaluating neuromuscular function during multijoint isometric tasks through only GRF data is associated with limitations ([20]). For example, Hahn ([20]) investigated lower-body biomechanics during multijoint isometric leg extensions and observed that changes in GRFs were not directly associated with changes in net joint moments (NJMs) as the positions of the lower body were altered through the full range of knee and hip motion. For example, although some subjects showed similar GRFs, the ratios between hip and knee NJM were different, which suggests that the GRF did not reveal any information about joint-specific contributions (e.g., hip vs. knee dominant contribution). Thus, analyses of biomechanical and neuromuscular function at the joint level (e.g., NJMs) may provide more detailed information than analysis of only the GRFs. To date, no study has examined NJMs during isometric pulling exercises, and the effects of changing body position and joint angles on the NJM of the lower body are not known. However, if changes in bar positions also influence NJMs in addition to the GRFs, and if their respective contributions to peak isometric pulling forces change, then this information might provide valuable information for practitioners and researchers who use such data to assess and monitor maximal force-producing capacity of the lower body.

Given that changing joint angles affects muscle lengths and internal moment arms, it is highly likely that these changes would influence the maximum moment-generating capacities of these muscles. Considering the implications that follow, it is also likely that the relative muscular effort (RME), which is often defined as the ratio between the inverse dynamics-based NJMs and the maximal theoretical moment based on the moment-angle curve, of these muscle groups would also differ with changes in joint angles and bar position. With respect to changing joint angles during a multijoint isometric task, it is therefore also possible that the RME of the respective muscle groups are also affected, perhaps even to a greater extent than the NJM. Because RME reflects the operating capacities of specific muscle groups, investigating lower-body RME in addition to NJMs during isometric pulls would provide important supplemental information about the relative functional demand imposed on each muscle group and its respective contribution to overall maximal force generation ([6,7]). Furthermore, knowledge about the functional demands and respective contributions across bar positions would offer practitioners insight into whether maximal GRFs during isometric pulls reflect general lower-body strength or joint-specific strength. The purpose of this study was to study the influence of bar position on joint-level biomechanics and GRFs during different isometric pulls. We hypothesized that peak ankle, knee, and hip NJMs and RME would differ depending on the bar position. The goal of this research was to provide evidence-based insights about the effect of bar position on joint-specific demands and operating capacities during isometric pulling exercises to provide detailed information for researchers and practitioners to better use data from isometric pulls to assess and monitor maximal strength.

Methods

Experimental Approach to the Problem

To identify the effect of bar position on joint-level biomechanics and GRFs during isometric pulling exercises, subjects performed maximal isometric pulls at 3 different bar positions while motion capture and GRF data were recorded. The peak internal NJMs at the ankle, knee, and hip joint were calculated with inverse dynamic analysis. Relative muscular effort was calculated as the ratio between the inverse dynamics NJMs and the maximum possible NJMs, which were estimated with regression-based maximum moment-angle models, and used to assess joint-specific force-production capacity. Given that moment-angle curves vary dynamically throughout a joint's range of motion, the 3 bar positions were chosen to reflect a wide range of hip and knee flexion angles. Because the mid bar position was based on the posture most used in IMTP testing ([5,8]), the low and high bar positions simply represented deviations where the bar was lowered or raised, respectively. The peak ankle, knee, and hip NJMs and RME at 3 different bar positions were compared to determine the effect of bar positions on lower-body NJMs and RME during the isometric pulls.

Subjects

Eight female NCAA Division I lacrosse athletes (age: 20 ± 2 years; height: 1.70 ± 0.03 m; and body mass: 65.4 ± 5.9 kg; No subjects were under 18) were therefore recruited for this study. Each player provided written informed consent, which was approved by the Marquette University's IRB. Data collection for the current study occurred after the end of the player's offseason training program, which included dynamic and isometric resistance training exercises. In addition, all players were familiar with IMTP test procedures through participation in previous research studies.

Procedures

Reflective markers were attached to various anatomical landmarks, and marker clusters were attached to the thighs, shanks, and feet of both legs (Figure 1). Specifically, markers were attached to the cervical vertebrae, acromion process, anterior superior iliac spine, posterior superior iliac spine, iliac crest, greater trochanter, femoral lateral epicondyle, femoral medial epicondyle, fibula head, tibia tuberosity, medial malleolus, lateral malleolus, calcaneal tuberosity, styloid process of fifth metatarsal bone, head of fifth metatarsal bone, head of first metatarsal bone.

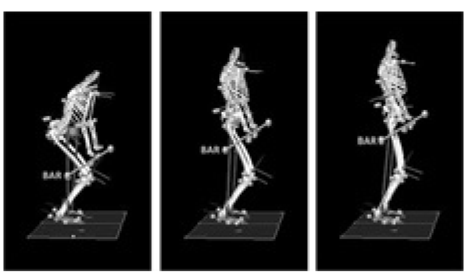

Figure 1.: Illustration of the marker set and isometric pulls set-up during the low (left), mid (middle), and high (right) testing positions. Low (left) and high bar (right) positions were variation from the mid bar position (middle – a posture matches the second pull of the clean).

Each player performed a standardized dynamic warm-up that consisted of simple callisthenic exercises and several submaximal and maximal jumping tasks. For the isometric pull testing, each subject performed 3 repetitions of each pull at 3 different bar positions (Figure 1), which were presented in a random order. Only joint angles during the mid bar position were standardized across players. For the IMTP position, a goniometer was used to position players such that their knee and hip angles were approximately 135° and 145°, respectively ([18]). During the low bar position, the bar was lowered so that it was positioned just above the knee joint (i.e., patella). During the high bar position, the bar was raised so that it was positioned close to the crease of the hip joint. At each position, subjects first performed 2 submaximal efforts and then 3 maximal efforts. During each maximal effort, subjects were instructed to pull on the bar as hard as possible for at least 3 seconds and received strong verbal encouragement.

Data Analysis

Kinematic data were collected with a 14-camera motion capture system (Vicon 612; Vicon, Los Angeles, CA) at 100 Hz. Kinetic data were recorded with 2 portable force plates (Kistler, Winterthur, Switzerland) at 1,000 Hz. The portable force plates were placed on an IMTP rack (Kairos Strength, Murphy, NC). Motion capture and force plate data were synchronously collected with a commercial software system (Vicon Nexus 1.8.2; Vicon, Los Angeles, CA). All data were exported as.c3d files and processed with Visual 3D software (C-Motion, Inc, Rockville, MD).

Kinematic and kinetic data were filtered with a fourth-order low-pass Butterworth filter at a cutoff frequency of 8 Hz, which was determined based on a residual analysis of the NJM data. The filtered data were used as input to a custom biomechanical model that consisted of trunk, pelvis, thigh, shank, and foot segments. A static trial was used to define segment coordinate systems based on anatomical markers of the proximal and distal ends of each respective segment. Joint angles during the static trial were defined as 0° at the ankle and 180° at the knee and hip joint. A standard inverse dynamic analysis was then used to combine kinematic, kinetic, and anthropometric data to calculate the internal NJMs at the ankle, knee, and hip joint (Figure 2).

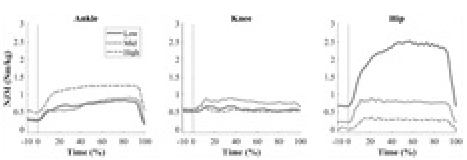

Figure 2.: Ankle (left), knee (middle), and hip (right) net joint moments [NJMs (N·m·kg^{-1})] from one subject during isometric pulls at the 3 different bar positions (solid line = low; dotted line = mid; and dashed line = high).

The peak gross GRFs (i.e., including body weight) and peak NJMs were extracted from the pull phase, where the onset was defined based on a threshold of the baseline mean plus 5 SDs ([8,12]). The ankle, knee, and hip joint angles at the time of peak NJMs were also extracted for analysis. The joint angles were combined with a regression model to calculate the maximum possible NJMs of the ankle, knee, and hip extensor muscles based on the moment-angle curves for each of these muscle groups ([1]). The regression-based estimates of the maximum possible NJMs were scaled to the height and mass of each player ([1]). Given that the pulling tasks were all isometric assessments, the joint angular velocities within the regression model were set to zero. Relative muscular effort was then calculated as the ratio between the inverse dynamics NJMs and the maximum possible NJMs. Although all dependent variables were calculated for each leg individually, the data from the left and right leg were averaged for statistical analysis. Moreover, data were averaged across each of the 3 trials at each of the 3 respective pull positions. The peak NJMs and peak GRFs were normalized to body mass (e.g., N·m·kg^{-1}).

Statistical Analyses

Within-session reliability of each dependent variable was assessed by calculating the intraclass correlation coefficients (ICCs) and the associated 95% confidence intervals (Table 1) ([2,16,22,24]). Intraclass correlation coefficient data were interpreted as poor (<0.5), moderate (0.5 to <0.75), good (0.75 to <0.90), and excellent (≥0.90) ([24]). Coefficients of variation data were also calculated (Table 2) and interpreted as either good (<5%), moderate (5% to <10%), or poor (>10%) ([16]). Three separate 2-way analyses of variance (ANOVA) were performed to investigate the effects of bar position (low, mid, and high) and joint (ankle, knee, and hip) on the NJMs, RME, and angles. The effects of bar position on GRF were investigated with a 1-way analysis of variance. Bar position and joint were treated as repeated measures. Post-hoc comparisons were made with paired *t*-tests. Significant differences in means of pair-wise comparisons are supplement with 95% confidence intervals and Hedges *g* effect sizes, which were interpreted as either small = 0.20–0.49, moderate = 0.50–0.79, and large ≥0.80, respectively ([21,25]). The level of statistical significance for the ANOVA was set to an α-level of 0.05. The α-level was adjusted with Bonferroni corrections in the case of multiple comparisons (e.g., among all 3 joints; α-level = 0.017). All statistical comparisons were performed in SPSS 26.0 (IBM Corp, Armonk, NY).

Table 1 - Within-session reliability [intraclass correlation coefficient (ICC {95% CI})] of the peak net joint moments (NJMs), relative muscle effort (RME), joint angle, and peak ground reaction forces (GRFs) across the 3 different bar positions (low, mid, and high).

Variables		**Bar position**		
		Low	**Mid**	**High**
NJMs	Ankle	0.81 (−0.24–0.99)	0.83 (0.12–0.98)	0.96 (0.81–0.99)
	Knee	0.76 (−0.56–0.98)	0.95 (0.77–0.99)	0.98 (0.93–1.00)
	Hip	0.95 (0.69–1.00)	0.96 (0.81–1.00)	0.89 (0.55–0.98)
RME	Ankle	0.62 (−1.49–0.97)	0.79 (−0.08–0.98)	0.96 (0.82–0.99)
	Knee	0.60 (−1.63–0.97)	0.97 (0.82–1.00)	0.99 (0.94–1.00)
	Hip	0.96 (0.74–1.00)	0.96 (0.81–1.00)	0.89 (0.54–0.98)
Angle	Ankle	0.99 (0.92–1.00)	0.99 (0.94–1.00)	0.98 (0.94–1.00)
	Knee	0.95 (0.77–0.99)	0.98 (0.91–1.00)	0.99 (0.97–1.00)
	Hip	0.94 (0.71–0.99)	0.98 (0.91–1.00)	0.89 (0.61–0.98)
GRFs	Vertical	0.94 (0.68–0.99)	0.91 (0.62–0.99)	0.77 (0.13–0.96)

Table 2 - Coefficient of variation (CV) and 95% confidence intervals (CIs) of the peak net joint moments (NJMs), relative muscle effort (RME), joint angle, and peak ground reaction forces (GRFs) across the 3 different bar positions (low, mid, and high).

Variables		**Bar position**		
		Low	**Mid**	**High**
NJMs	Ankle	0.15 (0.10–0.34)	0.26 (0.16–0.62)	0.33 (0.21–0.85)
	Knee	0.19 (0.12–0.43)	0.35 (0.22–0.92)	0.35 (0.22–0.91)
	Hip	0.16 (0.10–0.37)	0.29 (0.18–0.70)	0.42 (0.26–1.17)
RME	Ankle	0.12 (0.08–0.27)	0.27 (0.17–0.64)	0.33 (0.21–0.85)
	Knee	0.11 (0.07–0.24)	0.29 (0.18–0.71)	0.27 (0.17–0.66)
	Hip	0.18 (0.12–0.42)	0.29 (0.18–0.70)	0.40 (0.25–1.10)
Angle	Ankle	0.46 (0.29–1.19)	0.56 (0.34–1.62)	0.90 (0.50–5.24)
	Knee	0.21 (0.14–0.44)	0.26 (0.17–0.57)	0.47 (0.30–1.24)
	Hip	0.11 (0.07–0.22)	0.40 (0.25–0.97)	0.60 (0.37–1.85)

GRFs	Vertical	0.07 (0.05–0.15)	0.05 (0.03–0.11)	0.08 (0.05–0.16)

Results

Net Joint Moments

The statistical analysis indicated a significant interaction effect ($p = 0.001$; $\eta^2 = 0.877$) between joint and position on NJMs. Post-hoc tests indicated that pair-wise comparisons between the hip and ankle (*difference* = 1.43 (1.07–1.80); $p = 0.001$; $g = 4.02$), and the hip and knee (*difference* = 1.58 (1.26–1.91); $p = 0.001$; $g = 4.41$), NJMs differed in the low bar position (Figure 3). In addition, pair-wise comparisons across bar position indicated that knee NJMs were greater in the mid than high position (*difference* = 0.46 (0.20–0.71); $p = 0.005$; $g = 1.01$), and hip NJM differed across all pair-wise comparisons of bar position (low vs. mid: *difference* = 1.49 (1.16–1.82); $p = 0.001$; $g = 3.67$, low vs. high: *difference* = 1.90 (1.59–2.22); $p = 0.001$; $g = 4.90$, mid vs. high: *difference* = 0.42 (0.21–0.62); $p = 0.002$; $g = 1.34$). Ankle NJMs did not change with bar position.

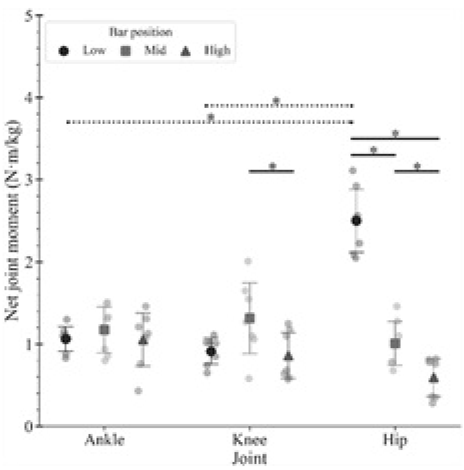

Figure 3.: Mean ± *SD* peak ankle, knee, and hip net joint moments (NJMs: N·m·kg^{-1}) for all subjects during isometric pulls at 3 different bar positions (circle = low; square = mid; and triangle = high). Note: for statistical comparisons, solid lines are used to indicate differences because of bar position, whereas dotted lines are used to indicate differences between joints. *Significance $p < 0.017$.

Relative Muscular Effort

The statistical analysis indicated a significant interaction effect ($p = 0.001$; $\eta^2 = 0.740$) between joint and position on RME. Post-hoc tests indicated that in the low bar position knee, RME was lower than ankle (*difference* = 0.24 (0.16–0.31); $p = 0.001$; $g = 3.49$) and hip (*difference* = 0.41 (0.29–0.53); $p = 0.001$; $g = 3.37$) RME. In the mid position, hip RME was less than knee (*difference* = 0.21 (0.06–0.36); $p = 0.014$; $g = 1.26$) RME. In the high position, hip RME was less than ankle (*difference* = 0.40 (0.14–0.66); $p = 0.010$; $g = 2.07$) and knee (*difference* = 0.25 (0.12–0.38); $p = 0.003$; $g = 1.84$) RME (Figure 4). In addition, pair-wise comparisons across bar position indicated that knee RME was smaller (*difference* = 0.22 (0.08–0.35); $p = 0.008$; $g = 1.51$) in the low than the mid bar positions, and hip RME differed across all bar positions (low vs. mid: *difference* = 0.40 (0.31–0.49); $p = 0.001$; $g = 2.73$, low vs.

high: *difference* = 0.54 (0.43–0.65); $p = 0.001$; $g = 3.84$, mid vs. high: *difference* = 0.14 (0.06–0.22); $p = 0.005$; $g = 1.18$).

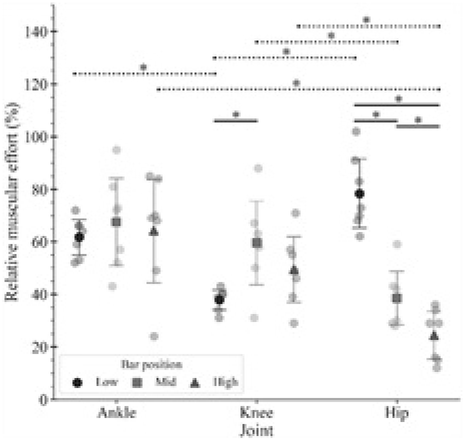

Figure 4.: Mean ± *SD* ankle, knee, and hip relative muscular effort (RME: %) for all subjects during isometric pulls at 3 different bar positions (circle = low; square = mid; and triangle = high). Note: for statistical comparisons, solid lines are used to indicate differences because of bar position, whereas dotted lines are used to indicate differences between joints. *Significance $p < 0.017$.

Ground Reaction Force

The statistical analysis indicated a significant main effect ($p = 0.002$; $\eta^2 = 0.599$) of bar position on peak vertical GRF (Figure 5). Post-hoc tests indicated that GRFs were significantly greater (*difference* = 2.52 (1.10–3.95); $p = 0.004$; $g = 1.27$) in the mid bar position than the high bar position (Figure 5).

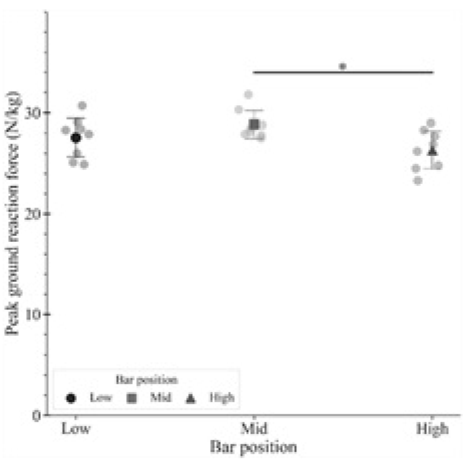

Figure 5.: Mean ± *SD* peak ground reaction force (GRF: $N \cdot kg^{-1}$) for all subjects during isometric pulls at 3 different bar positions (circle = low; square = mid; and triangle = high). Note: for statistical comparisons, solid lines are used to indicate differences because of bar position. *Significance $p < 0.017$.

Joint Angle

The statistical analysis indicated a significant interaction effect ($p = 0.001$; $\eta^2 = 0.905$) between joint and position on lower-body angles. Post-hoc tests indicated that ankle angles in the mid bar position were significantly greater (*difference* = 6.46 (3.57–9.35); $p = 0.001$; $g = 0.66$) than in the high bar position (Figure 6). In addition, post-hoc tests also indicated that all pair-wise comparisons for hip angles differed significantly such that joint angles progressively increased from the low to mid (*difference* = 32.01 (25.57–38.44); $p = 0.001$; $g = 3.26$) and mid to high (*difference* = 9.68 (6.76–12.60); $p = 0.001$; $g = 0.83$) bar positions and that all pair-wise comparisons for knee angles differed significantly such that joint angles progressively increased from the low to mid (*difference* = 10.54 (6.80–14.28); $p = 0.001$; $g = 0.83$) and mid to high (*difference* = 14.77 (9.09–20.44); $p = 0.001$; $g = 1.05$) bar positions.

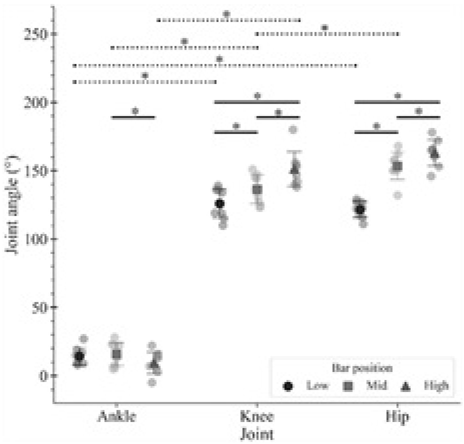

Figure 6.: Mean ± *SD* ankle, knee, and hip joint angles (°) for all subjects during isometric pulls at 3 different bar positions (circle = low; square = mid; and triangle = high). Note: for statistical comparisons, solid lines are used to indicate differences because of bar position, whereas dotted lines are used to indicate differences between joints. *Significance $p < 0.017$.

Discussion

The purpose of this study was to study influence of bar position on ankle, knee, and hip biomechanics and GRFs during different isometric pulls. The results indicated that bar position significantly influences GRFs as well as peak hip and knee NJMs and RME. Peak GRFs were significantly greater in the mid bar position than the high bar position, but did not differ between the low and mid bar position. Notably, hip NJMs differed from knee and ankle NJMs in the low bar position but were similar in the mid and high bar positions. Furthermore, the low bar position was associated with large hip and small knee RME, whereas the reverse was true for the mid bar position. Collectively, these results suggest that the low bar position is associated with larger hip NJMs and RME, whereas the mid bar position is characterized by larger knee and ankle RME despite similar NJMs. The interpretation of these findings has significant practical implications for the interpretation of isometric pulling data and its use in assessing and monitoring neuromuscular function of the lower body.

A primary finding of the current study was that bar position significantly influenced peak NJMs at the hip, knee, and ankle joints. More specifically, in the low bar position, the NJMs were largest at the hip, whereas in the mid and high bar positions, NJMs were generally more similar. Another finding was that hip NJMs were markedly influenced by bar position such that they differed across all positions. By contrast, although knee NJMs were greater in the mid bar position than in the high bar position, knee and ankle NJMs did not change much across bar positions. Although no previous study investigated the effects of manipulating body or bar position on joint-level demands during the isometric pulls, several studies showed that such manipulations were associated with changes in the production of peak GRFs.

For example, Guppy et al. ([17]) found that an upright torso with the bar in the second pull position enabled subjects to produce the greatest IMTP GRF among 4 different testing positions. Similarly, Beckham et al. ([4]) found subjects produced greater IMTP GRF with hip angles set to 145° than set to 125°. Although in the current study we varied bar position rather than joint angles, the mid bar position was characterized by hip (155°) and knee (135°) joint angles that were similar to body positions reported to be more favorable for maximizing GRFs ([4,17]). The GRF results of the current study partially agree with previous observations in that subjects produced greater GRFs in the mid than the high bar position, although no differences existed between the low and mid bar position. It should be noted that the GRF differences between mid and high bar positions were accompanied by differences in knee and hip NJM. However, although GRFs did not differ between the low and mid bar positions, hip NJMs still differed significantly. These divergent findings underscore that peak GRF magnitudes during the IMTP do not necessarily reflect maximal NJMs, and that GRFs are the result of joint-specific contributions and position-dependent functional trade-offs.

To further investigate the influence of bar position on lower-body biomechanics, the current study used a simple musculoskeletal model to estimate the maximal possible NJMs from regression-based moment-angle curves and combined this information with the inverse dynamics calculated NJMs during the isometric pulls into joint-specific estimates of RME ([1]). The findings of the current study indicated that hip, knee, and ankle RME differed significantly across bar positions. Specifically, the low bar position was associated with large hip and small knee RME values, whereas the mid and high bar positions were associated with large knee and small hip RME values. By contrast, ankle RME remained relatively constant across bar positions. These results suggest that performing the isometric pulls with the bar in the low bar position is associated with greater functional relative demand from the hip extensor muscles because these muscles operate closer to their maximum moment-generating capacity. In turn, the results suggest that knee extensor and ankle plantarflexor muscles operate closer to their maximum capacity during the mid and high bar positions. It is interesting to note that although none of the NJMs in the mid and high bar positions differed between joints, the RME of the hip extensors varied significantly between all bar positions and was lowest in the high bar position. Taken together, the RME results indicate that the performing isometric pulls with the bar in the mid position (i.e., knee at 135° and hip at 155°), which aligns with the literature-based recommendations for the IMTP, should be considered a test of knee extensor and ankle plantarflexor strength because these muscle groups are operating closer to their relative maximum capacity and thus seem to contribute most to the GRFs. Because neither the mid or high position elicit large NJMs or RME at the hip, a corollary is that performing the isometric pulls with the bar in these positions provides an assessment of only knee and ankle extension strength but not total or lower-body strength as often purported ([10]). Because the IMTP is used in assessing and monitoring maximum force producing capacity of the lower body, the practical implications of these findings suggest that the maximal GRFs generated during the IMTP reflect joint-specific strength, which depends on bar position and posture, rather than general lower-body strength as sometimes purported ([10]). Furthermore, the notion that IMTP performance provides information about joint-specific strength may be relevant when interpreting the presence or lack of cross-sectional correlations between the peak GRFs generated during the IMTP and performance in other functional activities (e.g., vertical jumping or change-of-direction tasks). The same notion should also be kept in mind when interpreting training-related changes in peak IMTP GRF and whether those changes explain improvements in functional activities, which in turn may be determined by, or subject to, joint-specific contributors.

This study is not without limitations, and the interpretations of the current results should be considered in light of these. First, NJMs represent the sum of moments generated by the muscle forces of all agonists and antagonists that cross the respective specific joint. This implies that individual muscle forces or the effects of cocontraction were not considered, which likely means that the NJMs underestimate the absolute magnitudes of muscular contributions during isometric pulls. Second, the maximum possible NJMs in the RME equation was calculated from moment-angle curves that were derived from isokinetic dynamometry and reported in previous studies. Although the moment-angle data and maximal NJM estimates were scaled by each player's body mass and height, it is possible that the reported RME values may not entirely represent the true RME of each of the extensor muscle groups, which may affect the joint-based comparison of RME. However, this limitation would not affect the bar position-based results because any errors in scaling maximum NJMs based on the regression equations would be consistent across bar positions. To address these limitations, future studies should therefore use more sophisticated musculoskeletal and computational models to further investigate how joint level, or even muscle level, biomechanics change based on bar position during isometric pulls. Finally, the results and interpretations of the current study were based on a sample size of 8 subjects, which could be considered small, and may inadvertently affect the results. In addition to considering the level of statistical significance, researchers and practitioners should therefore also consider the effect size of the statistical comparisons because these were adjusted for small sample sizes.

Practical Applications

The current study showed that bar position affects the peak NJM and RME at lower-body joints. Researchers and practitioners may want to consider that using different bar positions during isometric pull testing changes the relative functional demands and respective contributions from the lower-body extensor muscle groups. Specifically, the low bar position was associated with large hip and small knee joint effort, whereas the reverse was true for the mid bar positions. Moreover, because joint-level biomechanics differed between the low and mid bar positions, whereas the GRFs did not, the joint-specific demands and contributions to peak isometric pulling forces likely reflected a trade-off between hip dominance and knee dominance in the low and mid bar position, respectively. Practitioners should therefore be mindful of this trade-off when interpreting isometric pull data and using it to assess and monitor maximal force-producing capacity of the lower body. Similarly, researchers should be mindful of this trade-off when interpreting correlations or training-related changes in GRF performance in relation to performance of other strength and conditioning tasks.

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