INDUCED ACCELERATION ANALYSIS IN WEIGHTLIFTING: A PILOT STUDY

Kristof Kipp, Nayun Ahn

Department of Physical Therapy, Marquette University, Milwaukee, USA

The purpose of this pilot study was to determine the functional roles of the lower extremity joints during a weightlifting exercise. One participant performed the power clean exercise with 75% of one-repetition maximum while 3D motion capture and force plate data were recorded. Net joint moments were calculated via inverse dynamics analysis and used as inputs to an induced acceleration analysis that calculated joint-specific contributions to ground reaction forces (GRF). Results showed that all joints exhibited to phase-specific contributions to vertical GRF. Interestingly, the ankle plantarflexors produced primarily anterior GRF, whereas the knee extensors produced primarily posterior GRF. The results underscore joint- and phase-specific contributions to the production of vertical and horizontal GRF during the power clean.

KEYWORDS: sports, biomechanics, power clean, ground reaction forces.

INTRODUCTION: The control and coordination of ground reaction forces (GRF) are important aspects that reflect technique and performance of weightlifting exercises (Kipp & Giordanelli, 2018; Safrushahar et al., 2002). Specifically, the patterns of the vertical GRF are associated with vertical velocity and acceleration patterns of the barbell (Enoka, 1979; Kipp & Harris, 2014; Krol, 2001). Furthermore, Baumann et al. (1988) identified strong correlation (r = 0.97) between peak vertical GRF and the total mass of the lifter and barbell system. While the link between vertical GRF and weightlifting technique and performance is intuitive, much less is known about the role of horizontal GRF.

Horizontal GRF along with anterior-posterior changes in the centre of pressure during weightlifting exercises are considered a necessary element of weightlifting technique (Garhammer & Taylor, 1984). However, excessive horizontal motion of the barbell or displacement of the lifter during weightlifting exercises are generally considered undesirable and considered technical faults that may limit weightlifting performance (Kipp & Meinerz, 2017, Schilling et al., 2002). Precise control of the horizontal as well as vertical GRF may thus provide insight about technical efficiency. While the GRF reflect the dynamics of the combined lifter and barbell system, they do not provide insight about joint-specific function during the task. Knowledge about joint kinetics, however, provides meaningful information for athletes, coaches, and sports biomechanists because it helps identify different technical styles and offers insight into the neuromuscular demands during maximal effort lifts (Baumann et al., 1988; Kipp et al., 2012). It might therefore be of pragmatic interest to determine how joint kinetics, such as net joint moments (NJM), contribute to GRF.

One method to quantify the contribution of joint-specific NJM to GRF is via induced acceleration analysis (IAA), which decomposes the horizontal and vertical GRF into the force contributions that arise from the NJM of each joint while also accounting for gravitational and inertial forces. The purpose of this study was to determine the functional roles of the lower extremity joints during a weightlifting exercise. We hypothesized that the vertical and horizontal GRF would result from joint and phase specific contributions from the three primary extensor muscle groups of the lower extremity (hip, knee, and ankle) during the clean.

METHODS: One male participant (height: 1.91 m; mass: 95 kg; 75 kg one-repetition maximum [1-RM] power clean) participated in the current pilot study. The participant performed the power clean exercise with 60 kg (75% 1-RM) of his one-repetition maximum while motion capture and force plate data were recorded. Thirty-six individual markers were attached bi-laterally to the lower body and two markers were attached on the long ends of the barbell. Marker data were recorded at 100 Hz with 14 motion capture cameras while GRF were recorded at 1000 Hz from two force plates (one underneath each foot). All data were smoothed with a 4^{th} order low-pass

recursive Butterworth filter. The cut-off frequency for the filter was set to 6 Hz, which was determined based on a residual analysis.
Lower body joint angles were calculated via an inverse kinematics (IK) model. The IK had the pelvis segment as its root and constrained all translation degrees of freedom at the hips, knees, and ankles. The rotational degrees of freedom of the IK model included all three rotations at the hip, flexion/extension at the knee, and plantar/dorsi-flexion and inversion/eversion and at the ankle. NJM were calculated via inverse dynamics analysis and normalized by body mass.
The respective NJM were used as inputs to an IAA pipeline that calculated joint-specific contributions to the vertical and horizontal ground reaction forces (GRF) (Joao & Veloso, 2013). All calculations were performed in Visual3D software. Time-series data were trimmed to the period between when the vertical GRF exceeded the total weight of the system (i.e., barbell weight + participant weight) and when they fell below 30 N, which occurred just before the lifter's feet left the ground in preparation for the catch phase. The pull phase was further divided into the first pull, transition, and second pull phases based on the extension-flexion-extension pattern of the knee joint that characterizes the double knee bend technique in weightlifting (Baumann et al., 1988; Kipp et al., 2012).
The sum of the joint-induced GRF were qualitatively and quantitatively compared against the experimental GRF to validate the IAA analysis. The qualitative and quantitatively comparisons included visual inspection and calculation of the normalized root mean square error (nRMSE), respectively. The functional roles of the ankle, knee, and hip joints during the weightlifting exercise were determined based on their contributions to the vector components of the GRF throughout the entire pull phase. Although data were collected and calculated for both legs, only data from the right leg were analysed for the current pilot study.

RESULTS: The kinematic and kinetic joint data indicated that the participant used the double knee bend technique with clearly defined first and second pull phases (Figure 1).

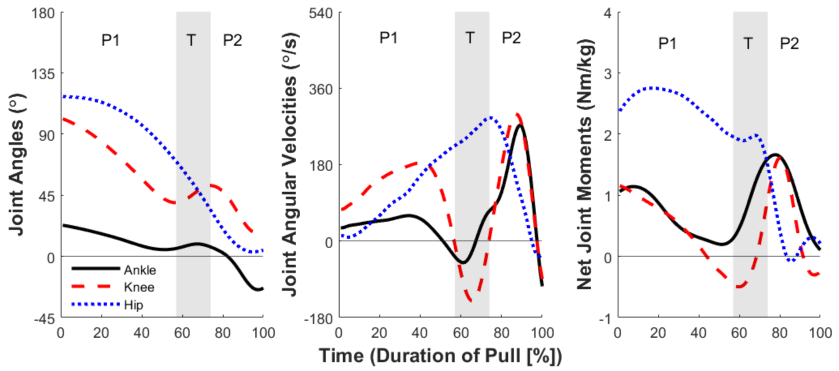

Figure 1: Ankle, knee, and hip joints angles, angular velocities, and net moments during the pull phases of the power clean. Positive angles represent flexion, with 0 representing hip and knee extension and neutral ankle position. Positive/negative joint angular velocities indicate extension/flexion velocities and positive/negative net joint moments represent extension/flexion moments. P1 = first pull phase, T = transition phase, P2 = second pull phase.

The qualitative validation analysis suggested that the IAA results adequately represent the joint-specific GRF produced by the ankle, knee, and hip NJM (Figure 2). The nRMSE for vertical and horizontal GRF were 5.2% and 2.7%, respectively.
Further qualitative analysis of the time-series data suggests that the ankle plantarflexors exhibit the largest contribution to vertical GRF in a manner that was consisted with phase dependent fluctuations in GRF (Figure 3). In contrast, the hip extensors contributed primarily to vertical GRF towards the end of the first pull, whereas knee extensors contributed to positive (upward/propulsive) GRF during the first and second pull and to negative (downward/braking) GRF during the transition phase. In the horizontal direction, the ankle plantarflexors produced primarily anterior GRF, whereas the knee extensors produced primarily posterior GRF.

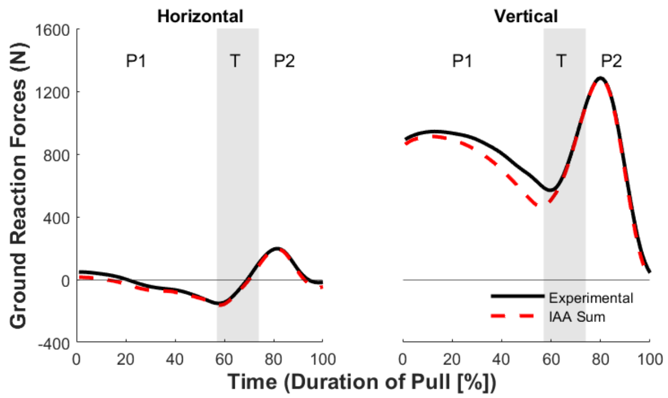

Figure 2: Vertical and horizontal sums of ground reaction forces produced by all three lower extremity joints (IAA Sum) and experimentally recorded ground reaction forces (Experimental). Data are from right leg only. P1 = first pull phase, T = transition phase, P2 = second pull phase.

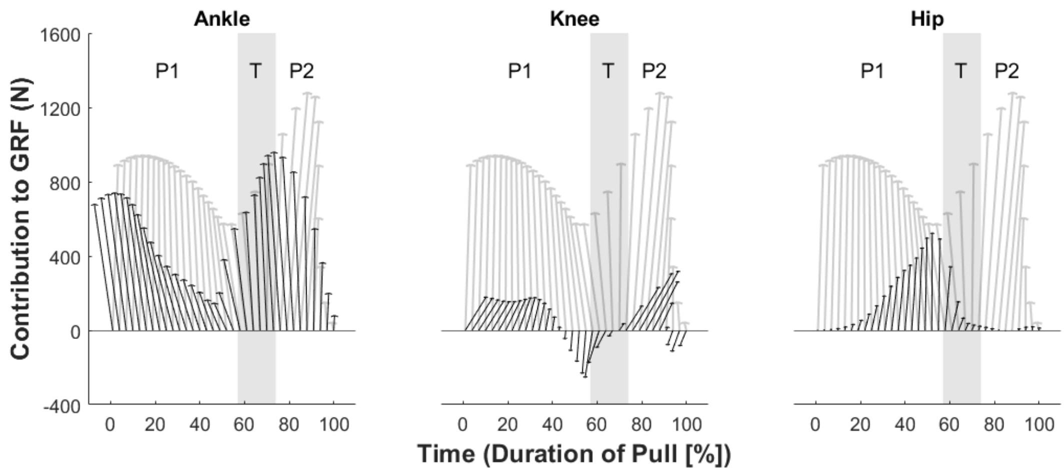

Figure 3: Ground reaction force (GRF) vectors produced by the ankle, knee, and hip net joint moments (NJM) during the pull phases of the power clean. Overall GRF vector shown in grey and individual joint-specific vector contributions shown in black. Data are from right leg only. Vector direction to the right indicates NJM contributions to GRF away from the lifter. P1 = first pull phase, T = transition phase, P2 = second pull phase.

DISCUSSION: The purpose of this study was to determine the functional roles of the lower extremity joints during a weightlifting exercise. The validation results suggest that the IAA adequately captured the joint-specific contributions to vertical and horizontal GRF. Subsequent analysis of these contributions to the magnitude and direction of the GRF vector identified how the respective joints produced propulsive and braking forces.

The NJM produced by the ankle plantarflexor and knee extensor muscles appeared to be the primary contributors to vertical propulsive GRF during the first and second pull, albeit the contribution from the ankle plantarflexor muscles were greater in magnitude. In addition, the knee joint muscles produced vertical braking GRF toward the end of the first pull phase. In contrast, the NJM produced by the hip extensor muscles appeared to contribute most to the vertical propulsive GRF towards the end of the first pull. Collectively, these results suggest that vertical propulsive GRF during the early parts of both the first and second pull phases are dominated by contributions from distal plantarflexor and extensor muscles, whereas the more proximal extensor muscles contribute primarily to the generation of vertical propulsive GRF toward the end of the first pull phase just as the knee extensor NJM begins to produce vertical braking forces. These results support previous findings that indicate that the beginning of the first pull is dominated by NJM contributions from the ankle and knee joint muscles and that the NJM contributions hip joint muscles become important towards the end of the first pull (Kipp, 2020), which is also where the hip joint muscles generate the greatest net joint powers. The current results also provide a novel perspective on the role of the hip extensor NJM as they appear to 'counterbalance' the vertical braking forces produced by the knee extensor NJM as the knee joint undergoes the second knee bend.

With respect to the horizontal GRF, the ankle plantarflexors produced primarily anterior GRF and the knee extensors produced primarily posterior GRF. These opposing patterns remained consistent during the first and second pull and thus indicate that the NJM generated by the ankle plantarflexor and knee extensor muscles function in concert to produce the overall horizontal GRF pattern. The horizontal GRF reflect the dynamics of the lifter and barbell system, which are important characteristics of successful weightlifting performance (Garhammer & Taylor, 1984; Gourgoulis et al., 2009). These results may therefore suggest that aberrant horizontal motion may result from uncoordinated ankle plantarflexor and knee extensor muscles function. Weightlifting biomechanics research may benefit from future projects that aim to determine if aberrant horizontal GRF and motions of the lifter and barbell system, such as during failed lifts (Gourgoulis et al., 2009), are the result of unbalanced contributions from either the ankle plantarflexor or knee extensor muscles.

The findings of the current study should be interpreted in light of a few limitations. First, the current investigation was a pilot study with one participant. It therefore remains to be seen if similar patterns are observed in other participants (e.g., with different strength or technique). It should be noted, however, that the participant used the double knee bend technique, which is the most common technique observed among weightlifters. Second, only a single lift was analysed, and intra-trial variations across either different loads or repeated lifts were not analysed. These limitations present further opportunities for future research.

CONCLUSION: In general, the results underscore that the production of GRF during the power clean is the result of coordinated control of ankle, knee, and hip joint muscles. More specifically, the results highlight the phase- and joint-specific contributions to vertical and horizontal GRF during the power clean.

REFERENCES

Baumann, W., Gross, V., Quade, K., … (1988). The snatch technique of world class weightlifters at the 1985 world championships. *International Journal of Sport Biomechanics*, *4*, 68-89.

Enoka, R. M. (1979). The pull in Olympic weightlifting. *Medicine & Science in Sports*, *11*, 131-137.

Garhammer, J., & Taylor, L. (1984). Center of pressure movements during weightlifting. In *ISBS-Conference Proceedings Archive*, 2.

Gourgoulis, V., Aggeloussis, N., Garas, A., … (2009). Unsuccessful vs. successful performance in snatch lifts: a kinematic approach. *The Journal of Strength & Conditioning Research*, *23*, 486-494.

Joao, F., & Veloso, A. (2013). Quantifying the effect of plyometric hopping exercises on the musculoskeletal system: contributions of the lower limb joint moments of force to ground reaction forces in hopping exercise. *Journal of Mechanics in Medicine and Biology, 13*, 1350027.

Kipp, K. (2020). Relative importance of lower extremity net joint moments in relation to bar velocity and acceleration in weightlifting. *Sports Biomechanics*, 1-13.

Kipp, K., & Giordanelli, M. D. (2018). Control And Regulation of Ground Reaction Forces During the Pull-Phase of the Snatch and Clean. *ISBS Proceedings Archive*, 36, 802.

Kipp, K., & Harris, C. (2014). Associations between ground reaction forces and barbell accelerations in weightlifting. In *ISBS-Conference Proceedings Archive*, 32.

Kipp, K., & Meinerz, C. (2017). A biomechanical comparison of successful and unsuccessful power clean attempts. *Sports Biomechanics*, *16*, 272-282.

Kipp, K., Redden, J., Sabick, M.B., ... (2012). Weightlifting performance is related to kinematic and kinetic patterns of the hip and knee joints. *Journal of Strength and Conditioning Research, 26*, 1838-1844.

Krol, H. (2001). The relationship between barbell velocity and ground reaction force of athlete-device system during the snatch. *Journal of Human Kinetics*, *6*, 73-79.

Safrushahar, Y., Hasan, N., Wilson, B. (2002). Biomechanical analysis of the snatch during weightlifting competition. In *ISBS-Conference Proceedings Archive*, 20.

Schilling, B. K., Stone, M. H., O'BRYANT, H. S., ... (2002). Snatch technique of collegiate national level weightlifters. *The Journal of Strength & Conditioning Research*, *16*, 551-555.