Hip Moment and Knee Power Eccentric Utilisation Ratios Determine Lower-Extremity Stretch-Shortening Cycle Performance

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Hip Moment and Knee Power Eccentric Utilisation Ratios Determine Lower-Extremity Stretch-Shortening Cycle Performance

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Abstract
The eccentric utilisation ratio (EUR) is calculated as the ratio between countermovement jump (CMJ) and squat jump (SJ) heights, and is an indicator of lower-extremity stretch-shortening cycle (SSC) performance in athletes. Joint-based EUR can also be calculated but have never been reported. The purpose of this study was to investigate whether jump height-based (JH-based) EUR can be predicted by joint-specific EUR. Nine NCAA Division I college athletes (age: 21 ± 1 year, height: 1.75 ± 0.15 m, mass: 71 ± 20 kg) performed three SJ and CMJ. During all jumps, kinematic and kinetic data were obtained and used to calculate hip, knee and ankle net joint moments (NJM) and net joint powers (NJP). JH was calculated from pelvis marker data. EUR (CMJ/SJ [unitless]) were calculated for JH, NJM, and NJP. JH-EUR was 1.11 ± 0.70. NJM-EUR were 1.07 ± 0.17, 1.17 ± 0.25, and 1.07 ± 0.18 for the hip, knee and ankle joint, respectively. NJP-EUR were 1.41 ± 0.12, 1.26 ± 0.28 and 1.06 ± 0.11 for the hip, knee and ankle joint, respectively. Regularised regression showed that Hip-NJM-EUR, Knee-NJP-EUR and Ankle-NJM-EUR were able to predict 83% of the variance in JH-EUR, which suggests that the enhancement of lower-extremity SSC performance during CMJ arises from a combination of these parameters.

Keywords
Biomechanics, LASSO, elastic net, countermovement jump, pre-stretch augmentation

Introduction
Sports scientists and strength and conditioning practitioners often measure and monitor parameters related to stretch-shortening cycle (SSC) function and performance, because effective use of the SSC is important for performance in several athletic activities and sports (Cronin, McNair, & Marshall, [5]; McGuigan, Cormack, & Gill, [12]; McGuigan, Doyle, Newton, & Edwards, [13]; McMaster, Gill, Cronin, & McGuigan, [14]). SSC performance is often assessed through various types of jumping exercises, such as the countermovement jump (CMJ) and the squat jump (SJ) (Cronin et al., [5]; McGuigan et al., [12], [13]; McMaster et al., [14]; Suchomel, Sole, & Stone, [18]). It is also common practise to calculate the ratio or per cent difference between the performance outcomes from these two exercises, because these variables purportedly provide information on how well an athlete utilises the SSC (Suchomel et al., [18]).

The eccentric utilisation ratio (EUR) represents the ratio between CMJ and SJ performance, and is commonly used as an indicator of lower-extremity SSC function in athletes (Cronin et al., [5]; McGuigan et al., [12], [13]; McMaster et al., [14]; Suchomel et al., [18]). JH-based (JH-based) EUR calculations have been used to monitor acute and chronic training responses, assess player- and position-specific differences in jump performance and guide the programme design process of individual athletes (Lloyd, Oliver, Hughes, & Williams, [9]; Markovic, [10]; McMaster, Gill, Cronin, & McGuigan, [15]; Oliver, Armstrong, & Williams, [16]; Secomb et al., [17]). For example, McMaster et al. ([15]) suggested that individuals with high EUR have maximised their SSC contribution to muscle force production and may thus benefit most from focused fast-concentric training, whereas individuals with low EUR may benefit most from SSC/plyometric training. This notion is supported by data from McGuigan et al. ([13]) who showed that the EUR increases from off-season to preseason training periods as players begin to focus more on sport-specific and plyometric-type exercises.
To augment the information that JH-based EUR provides, some authors also calculate EUR for other variables, such as peak force or power (McGuigan et al., [13]; Suchomel et al., [18]). One way to achieve this is to assess the mechanics of the centre-of-mass during the SJ and CMJ with a force plate, calculate the peak force or power for both types of jumps, and subsequently calculate the EUR (Suchomel et al., [18]). Some researchers even report that the power-based EUR is more sensitive in detecting training-related differences (McGuigan et al., [13]). That said, variables related to centre-of-mass mechanics, such as lower-extremity peak power or impulse are also associated with some limitations. For example, lower-extremity power correlates with jump performance in only some studies (Aragón-Vargas & Gross, [1]; Dowling & Vamos, [6]). In contrast, net mechanical impulse is a much better predictor of JH Kirby, McBride, Haines, & Dayne, [7]), but may not provide enough level of detail about jump strategies at the whole-body level (Aragón-Vargas & Gross, [1]). Peak net joint moments (NJM) and powers are better able to differentiate between good and bad jumpers (McMaster et al., [14]; Vanezis & Lees, [20]). Some of the equivocal and contrasting findings on JH-based EUR reported in previous studies may thus stem from limitations associated with lower-extremity measures of SSC performance because they do not adequately account for joint-level dynamics.

Although joint-level differences between CMJ and SJ have been reported (Bobbert & Casius, [2]; Bobbert, Gerritsen, Litjens, & Van Soest, [3]), joint-level EUR have never been calculated. This means that the joint-specific contributions to lower-extremity EUR are also not known. However, calculating joint-specific EUR and determining their contributions to lower-extremity EUR would help expand our understanding about neuromuscular control and biomechanical function of jumping exercises, and could provide novel and pragmatic insights for the programme design and training process. Furthermore, given that sports scientists and coaches often calculate lower-extremity EUR and use it to assess and monitor lower body performance it would be advantageous for them to know which joints or joint-level variables (e.g., joint moments or powers) contribute to lower-extremity EUR based on JH. The purpose of this study was therefore to determine the joint-based mechanical contributions of the hip, knee, and ankle EUR to lower-extremity (i.e., JH-based) EUR. We hypothesised that it would be possible to predict lower-extremity EUR from a combination of joint-level EUR variables.

**Methods**

**Participants**

Nine Division I university track and field and soccer athletes (age: 21 ± 1 year, height: 1.75 ± 0.15 m, mass: 71 ± 20 kg) participated in this study. The average plyometric training experience of the athletes was 4 ± 2 years. Before testing, all athletes were briefed on the scope of the study, and read and signed an informed consent document (HR-2659) that was approved by Marquette University’s Institutional Review Board for Human Subjects Testing.

**Procedures**

All athletes performed three SJ and CMJ. Athletes were positioned such that each foot was fully placed on one of two force plates. All athletes were well familiar with the testing procedures through participation in similar studies and testing protocols. Athletes held a wooden dowel (0.45 kg) on their shoulders and were asked to squat down to their preferred depth. For the SJ, they remained in this
position for 2–3 s before jumping as high as possible. For the CMJ, they jumped as high as possible immediately after reaching their preferred depth. Each athlete was given several warm-up jump attempts, during which they progressively increased CMJ height. Athletes then performed three maximal efforts SJ and CMJ with approximately 20–30 s rest between all jumps. The absence of a countermovement during the SJ was confirmed through visual inspection of the ground reaction force data in real-time. If a noticeable countermovement was noticed, the SJ was repeated.

During all jumps, kinematic and kinetic data were obtained from 14 reflective markers (Plug-in-Gait marker set) and two force plates, respectively. The positions of the reflective markers were recorded at 100 Hz with 14 VICON motion capture cameras (ViconMX, VICON, Centennial, CO, USA). Kinetic data were recorded at 1,000 Hz with two AMTI force plates (Models OR6-6, Advanced Mechanical Technologies Inc., Watertown, MA, USA) that were mounted flush with the floor. Kinematic, kinetic and basic anthropometric data were combined with a standard biomechanical model (Plug-in-Gait). The model uses a joint coordinate system and Cardan angles to calculate joint kinematics based on the flexion-abduction-rotation sequence. Body-mass normalised hip, knee and ankle NJM (N·m/kg) and net joint powers (NJP [W/kg]) of the right leg were calculated with this model (Figure 1 & 2). All model outputs were smoothed with a generalised cross-validatory spline (Woltring, [22]). JH was calculated as the peak displacement of the pelvis segment during each type of jump with respect to a normal standing position. The JH-based EUR's were calculated as the ratios between CMJ and SJ variables (CMJ/SJ [unitless]) from the peak JH data (i.e., JH-EUR). The joint-based EUR's were calculated as the ratios between CMJ and SJ variables from the peak concentric NJM and NJP data for each joint (e.g., Hip-NJM-EUR, Hip-NJP-EUR etc.). Three-trial averages were subsequently calculated for each variable and used for statistical analysis.
Figure 1. Sample net joint moment (NJM [Nm/kg]) data from a single countermovement jump (solid line) and squat jump (dashed line) trial. Top: Hip NJM, Middle: Knee NJM, Bottom: Ankle NJM
Figure 2. Sample net joint power (NJP [W/kg]) data from a single countermovement jump (solid line) and squat jump (dashed line) trial. Top: Hip NJM, Middle: Knee NJM, Bottom: Ankle NJP

Statistical analysis
The reliabilities of all variables were assessed with Intra-class correlation coefficients based on a two-way random model and the absolute agreement of average measures (Table 1). Normality was assessed with the Shapiro–Wilk test. Pearson product–moment correlation coefficients ($r$) were calculated between the independent (CMJ height) and dependent variables (JH-EUR and all joint-level EUR's). The strengths of the correlation coefficients were interpreted based on their magnitudes as follows: $0.10–0.29 =$ small, $0.30–0.49 =$ moderate, $0.50–0.99 =$ large (Cohen, [4]). The significance level for each correlation was set to 0.05.
Table 1. Intra-class correlations (and 95% confidence intervals) for jump height (JH), net joint moments (NJM), and net joint powers (NJP) during the squat jump (SJ) and counter-movement jump (CMJ)

<table>
<thead>
<tr>
<th></th>
<th>NJM</th>
<th>NJP</th>
<th></th>
<th>NJM</th>
<th>NJP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>JH</td>
<td>Hip</td>
<td>Knee</td>
<td>Ankle</td>
<td>Hip</td>
</tr>
<tr>
<td>SJ</td>
<td>0.999 (0.997–1.000)</td>
<td>0.891 (0.643–0.976)</td>
<td>0.931 (0.780–0.985)</td>
<td>0.988 (0.954–0.997)</td>
<td>0.984 (0.949–0.996)</td>
</tr>
<tr>
<td>CMJ</td>
<td>0.998 (0.995–1.000)</td>
<td>0.933 (0.656–0.986)</td>
<td>0.963 (0.856–0.991)</td>
<td>0.985 (0.950–0.996)</td>
<td>0.932 (0.784–0.983)</td>
</tr>
</tbody>
</table>
A regularised regression model was used to investigate the contributions of the joint-specific NJM- and NJP-EUR variables to JH-EUR. The model consisted of least absolute shrinkage and selection operator (LASSO) and elastic net regularisation. The LASSO regularisation performs variable selection and removes redundant variables, which serves to increase the accuracy and interpretability of regression models (Tibshirani, [19]). The elastic net regularisation helps deal with highly correlated predictor variables and improves the fit of regression models for data sets with many predictors and few observations (Zou & Hastie, [23]). All variables were standardised before being used as input to the model. The elastic net 'alpha' coefficient was set to 0.5, and the entire regularisation model was cross-validated five times across 100 'lambda' values. The model with the smallest cross-validated mean square error (MSE) was used to obtain regression coefficients for the predictor variables of a minimum MSE model. In addition, regression coefficients for the predictor variables of a sparser model were obtained from the minimum MSE model plus one standard error. The coefficients of determination (R²) and p-values for the minimum MSE model and sparser model were also calculated to gauge the model's goodness of fit and significance, respectively. All statistical analyses were performed in MATLAB 2015b (The Mathworks, Natick, MA, USA).

Results
Descriptive data are reported as Mean ± SD (Table 2). The correlation analysis showed that JH-EUR exhibited a large positive correlation with Knee-NJP-EUR (Table 3). The LASSO and elastic net regularisation for the minimum MSE and sparser model indicated that three and two joint-level EUR's variables were the most important predictors of JH-EUR, respectively (Table 4).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Joint</th>
<th>r</th>
<th>95% CI</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NJM</td>
<td>Hip</td>
<td>0.255</td>
<td>-0.594–0.776</td>
<td>0.244</td>
</tr>
<tr>
<td>Knee</td>
<td>0.501</td>
<td>-0.619–0.887</td>
<td>0.085</td>
<td></td>
</tr>
<tr>
<td>Ankle</td>
<td>0.358</td>
<td>-0.569–0.864</td>
<td>0.168</td>
<td></td>
</tr>
<tr>
<td>NJP</td>
<td>Hip</td>
<td>0.100</td>
<td>-0.761–0.868</td>
<td>0.386</td>
</tr>
<tr>
<td>Knee</td>
<td>0.685</td>
<td>0.175–0.954</td>
<td>0.021</td>
<td></td>
</tr>
<tr>
<td>Ankle</td>
<td>0.448</td>
<td>-0.493–0.919</td>
<td>0.102</td>
<td></td>
</tr>
</tbody>
</table>
Table 4. Predictor variables and regression coefficients (β) for the minimum MSE and sparser model derived from LASSO and elastic net regularisation

<table>
<thead>
<tr>
<th>Predictor Variables</th>
<th>β</th>
<th>R²</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum MSE Model</td>
<td></td>
<td>0.831</td>
<td>0.0006</td>
</tr>
<tr>
<td>Hip-NJM-EUR</td>
<td>0.275</td>
<td></td>
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<tr>
<td>Knee-NJM-EUR</td>
<td>0</td>
<td></td>
<td></td>
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<tr>
<td>Ankle-NJM-EUR</td>
<td>0.110</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip-NJP-EUR</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee-NJP-EUR</td>
<td>0.192</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ankle-NJP-EUR</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sparser Model</td>
<td>0.698</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>Hip-NJM-EUR</td>
<td>0.097</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee-NJM-EUR</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ankle-NJM-EUR</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip-NJP-EUR</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee-NJP-EUR</td>
<td>0.128</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ankle-NJP-EUR</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Discussion and implications

The purpose of this study was to determine the joint-level contributions of hip, knee and ankle joint mechanics in predicting lower-extremity (i.e., JH-based) EUR. The major finding of this study was that combinations of Hip-NJM-EUR, Knee-NJP-EUR and Ankle-NJM-EUR were able to account for between 70% and 83% of the variance in JH-EUR. Furthermore, comparison of the two regularised regression models indicated that Hip-NJM-EUR and Knee-NJP-EUR had a greater and more consistent influence on JH-EUR than Ankle-NJM-EUR. In combination, these results suggest that greater enhancement of lower-extremity SSC performance during the CMJ arises through a combination of large Hip-NJM and Knee-NJP.

The minimum MSE model indicated that greater enhancement of lower-extremity EUR is associated with greater hip and Ankle NJM during the CMJ than during the SJ. The result from this regularised regression model therefore suggest that the ability to effectively use the SSC at the level of the entire lower-extremity is in large part due to a person’s ability to produce large hip and ankle NJM during the CMJ. Bobbert et al. ([3]) previously reported that NJM during the first part of the range of joint extension of the CMJ were greater than during the SJ. Although these authors suggested that the enhancement of joint-level mechanics during the concentric phase of the CMJ over the SJ is attributed to a muscle’s greater active state and force output (Bobbert & Casius, [2]; Bobbert et al., [3]), they did not delineate between the contributions of different joints to the overall enhancement of CMJ performance over that of the SJ. Given that in the current study the EUR of the hip extensor and ankle plantarflexor NJM were correlated with JH-EUR, greater active state facilitation (i.e., force production) may thus be more pronounced at these joints during the CMJ compared to the SJ. In addition, previous research suggests that hip extensor NJM production is an important factor during sub-maximal and maximal CMJ and is a good discriminator of CMJ performance (Vanezis & Lees, [20]; Vanrenterghem, Lees, Lenoir, Aerts, & De Clercq, [21]). Since Ankle-NJM-EUR was not included in the sparser
regularised regression model, but the model still retained good prediction ability, it seems likely that the enhancement of ankle NJM during the CMJ is not as crucial of a contributor to the enhancement of JH-EUR. The results of the current study therefore underscore the importance of hip NJM, and in particular how they contribute to lower-extremity EUR and SSC performance.

The minimum MSE and sparser regularised regression model both indicated that greater enhancement of lower-extremity EUR is associated with greater knee NJP during the CMJ than SJ. Knee-NJP-EUR was the only variable that exhibited a large significant correlation with JH-EUR when only simple linear regressions were considered. Since Knee-NJP-EUR was a significant predictor of JH-EUR in the correlation and regression models, it appears to be the most robust predictor of lower-extremity EUR. Since knee NJP, and not knee NJM, was a better and more consistent predictor of lower-extremity EUR it may be that the knee extensor muscle group needs to balance NJM production with joint extension velocity to optimise NJP output in order to most effectively enhance SSC performance. Knee NJP is also an important contributor to drop jump performance, and exercise-related increases in knee NJP during the push-off phase of drop jumps after plyometric and power training correlate positively with improvements in drop JH (Kyröläinen et al., [8]). Interestingly, however, training-related increases in knee NJP during the push-off phase of drop jumps arise primarily from increases in knee NJM and not increases in knee joint extension velocity (Kyröläinen et al., [8]). Improvements in JH-EUR with training may thus reflect the knee joint muscle’s propensity towards improving and leveraging active state mechanics after plyometric and power training. This may also explain why plyometric training improves CMJ height to a greater extent than SJ height (Markovic, [10]; Markovic & Mikulic, [11]).

All in all, the results from this study suggest that greater Hip-NJM-EUR and Knee-NJP-EUR are associated with greater enhancement of lower-extremity SSC performance during CMJ. This information may yield important practical applications for sports scientists and coaches as it has been previously suggested that athletes with either a low or high EUR may benefit most from plyometric or fast-concentric training, respectively (McMaster et al., [15]). Furthermore, it appears possible to increase EUR with gradual shifts in the emphasis of training from general and strength-type exercises to more sport-specific and plyometric-type exercises, as characterised by typical transitions from offseason to preseason training (McGuigan et al., [13]). For coaches, the practical implications of the results of the current study suggest that athletes who exhibit low SSC enhancement during CMJ also exhibit low hip joint moment and knee joint power EUR, which raises the question whether these athletes might benefit from targeted and periodised plyometric training of the hip and knee extensor muscle groups to improve lower-extremity SSC performance. In this context, training to improve the capacity of the hip extensor muscles to generate large NJM and of the knee extensor muscles to produce large mechanical power outputs may help improve SSC enhancement during the CMJ. However, given the cross-sectional design of the current study, future studies should investigate the effects of such targeted interventions to see if these actually improve joint-specific and JH-based EUR.

There are some limitations to this study that should be considered when interpreting the results and considering the practical implications. First, the results from the correlation analysis and the associated practical implications are based on a relatively small sample size. It could therefore not be ruled out that the current study is underpowered. However, regularised regression models, such as elastic nets, perform much better in situations where sample sizes are small (Zou & Hastie, [23]). The consistency
between the results from the regularised regression and from the correlation analysis therefore suggests that some of the results are robust despite the small sample size. Second, JH calculations in the current study were based on the difference between hip markers during the standing position and during the apex of the CMJ and SJ. While the JH calculation method would not affect the EUR results, it may lead to discrepancies in JH comparisons from studies that calculate JH from force-time data. Third, we also did not control for the training or sport background of the athletes recruited for this study. Although previous research has shown that both variables can influence JH-EUR (McGuigan et al., [13]; McMaster et al., [15]) their influence on joint-level EUR is not known. Likewise, we also did not control for training phase, which could also affect JH-EUR, and it is conceivable that joint-level EUR differ between athlete populations and change with training. It is also possible that the contributions of joint-specific EUR to JH-EUR change as athletes engage in training. While these are all limitations with the current study, the absence of joint-based EUR data in the literature warranted an initial investigation, such as the current study. Future studies should therefore focus investigating how joint-specific EUR differ between group of athletes, change with various training programmes, and whether they ultimately provide better insight into SSC performance than global lower-extremity measures, such as JH-EUR.

Conclusion
The results suggest that the enhancement of lower-extremity SSC performance during the concentric phase of the CMJ primarily results from greater hip NJM and knee NJP outputs than during the SJ. The practical application of these results is that JH-based EUR provides practitioners with insight into mechanical function of the hip and knee joints, which may be of interest with respect to monitoring the performance levels and capacities of these joints. Further, the results implicate hip NJM and knee NJP and as potential targets for training interventions that aim to increase EUR and facilitate lower-extremity SSC performance. The veracity of the last statement should be the focus of future investigations, such as a training study. However, the results of the current study inform such future training studies in that emphasis should likely be placed on increasing the NJM output of the hip extensor muscles and increasing the NJP output of the knee extensor muscles.

Acknowledgments
We would like to acknowledge the Marquette University Sports Performance staff for their help with this project.

Disclosure statement
No potential conflict of interest was reported by the authors.

Footnotes
The research presented in this study was conducted at Marquette University

References


