RATE OF FORCE DEVELOPMENT AND TIME TO PEAK FORCE DURING PLYOMETRIC EXERCISES

R.L. Jensen[1], E.P. Flanagan[2], and W.P. Ebben[3]

Dept. HPER, Northern Michigan University, Marquette, MI, USA[1]
Biomechanics Research Unit, University of Limerick, Limerick, Ireland[2]
Program in Exercise Science, Marquette University, Milwaukee, WI, USA[3]

Rate of force development (RFD) during the first 100 and 250 msec of the positive acceleration phase of plyometric exercises and time to peak force were determined in 23 NCAA Div. I athletes. Subjects performed a countermovement jump (CMJ), cone hop (CH), tuck jump (TJ), single leg CMJ (SLJ), and squat jump with 30% 1 RM squat (SJ30) on a force platform. Results showed SLJ and SJ30 had lower RFD100 and higher time to peak force, while CH and TJ had higher RFD100 and shorter time to peak force ($p<0.05$). These findings are in agreement with previous research that shows that quick movement exercises have high RFD. However, RFD250 may be an inappropriate measure to classify very quick jumps, such as the CH, because RFD values approach zero or become negative when subjects are close to or already leaving the ground.

KEY WORDS: JUMPING, RFD, STRETCH SHORTENING CYCLE

INTRODUCTION:

The rate of force development (RFD) has been defined as the rate of rise of contractile force at the beginning of a muscle action (Aagaard et al., 2002). Schmidtbleicher (1992) has stated that RFD is manifested in short and long components of the stretch shortening cycle (SSC). The short component is believed to occur within 100 to 250 msec of the muscle activation, and when applied to the lower body, is characterized by small angular displacements of the ankle, knee, and hip joints such as during sprinting or quick jumping (Schmidtbleicher, 1992). The long component is typified by muscle activation of more than 250 msec and occurs in movements that involve larger angular displacement of the lower extremity joints during maximal vertical jumps (Schmidtbleicher, 1992). While initial and maximal RFD is thought to be expressed during activities such as sprinting and quick jumps, correlations between measures of RFD during 100 msec and performance are questionable (Wilson et al., 1995).

The stretch shortening cycle (SSC) involves the mechanical stretching of muscles and tendons immediately prior to rapid concentric contractions. Mechanisms proposed to contribute to the SSC include the neural potentiation of the contractile machinery during the eccentric phase and reflex contributions from the muscle spindle. The acute time course of these mechanisms and how they may influence RFD in a variety of different jumps, or plyometric exercises, is unclear. Flanagan (2007) has shown that a countermovement jump (CMJ) is a slow SSC movement, but one which maximizes jump height; while the drop jump is a faster, more explosive activity in which much greater peak ground reaction forces are developed. Performance enhancement in slow SSC activities appears more reliant on neural potentiation of the contractile machinery during the eccentric phase (Bobbert et al. 1996; Walshe et al., 1998). As a result, the slow and fast SSC may represent different action patterns, affecting performance in different ways. However, Ebben et al. (2007) reported that RFD was not related to maximal jump height or training status.

The RFD has been evaluated during a variety of isometric, resistance training, and weightlifting movements, but is not well understood during dynamic activities such as jumping. In addition to questions about RFD during dynamic movements, little information exists to describe the time course of the positive acceleration phase when propulsive force is developed during plyometric exercises involving a countermovement. Therefore, the purpose of the current study was to assess the RFD100, RFD250, and the duration of the positive acceleration phase of the movement described as the time to peak ground reaction force (tGRF).

METHODS:

Twenty three NCAA Div. I athletes (Mean ± SD: Age = 20.4 ± 2.4 y; 178.4 ± 9.3 cm; 92.8 ± 17.9 kg) participated in the current study. All subjects used the studied exercises in their regular resistance-training regimen. Subjects had performed no resistance training in the 48 hours prior to data collection and. Institutional Review Board approval was obtained and subjects signed an informed consent form prior to participating in the study.

Subjects performed a standardized warm-up prior to the collection of data. Before each exercise, subjects were given a visual demonstration and allowed to practice the appropriate technique. Following the warm-up subjects performed a countermovement jump (CMJ), cone hop (CH), tuck jump (TJ), single leg CMJ with the dominant leg (SLJ), and a squat jump with 30% 1 RM squat (SJ30) once in a randomized order. A one minute rest interval was maintained to ensure sufficient recovery between exercises. For the CH subjects were instructed to hop laterally over a 15 cm tall cone as quickly as possible. For all other exercises subjects were asked to jump as high as possible. Arm position was not controlled throughout the movements as it was desired to keep the plyometric exercises as close as possible to that experienced in the training environment to increase the external validity.

Ground reaction force (GRF) measurements were obtained for each plyometric exercise using a force plate BP 600-1200 AMTI, Watertown, MA, USA) sampling at 1000 Hz. Using the acquired GRF traces, the point when body weight was achieved after the countermovement was identified (see figure 1). Rate of force development was calculated as the force determined for either 100 msec (RFD100) or 250 msec (RFD250) from the point when the vertical force trace reached the subject's body mass after the countermovement phase of the exercise. Values were normalized to 1 second and expressed as N·sec^{-1}. Time to peak GRF was defined as the difference from the point when the vertical force trace reached the subject's body mass after the countermovement to the highest GRF attained during the positive acceleration phase of the movement.

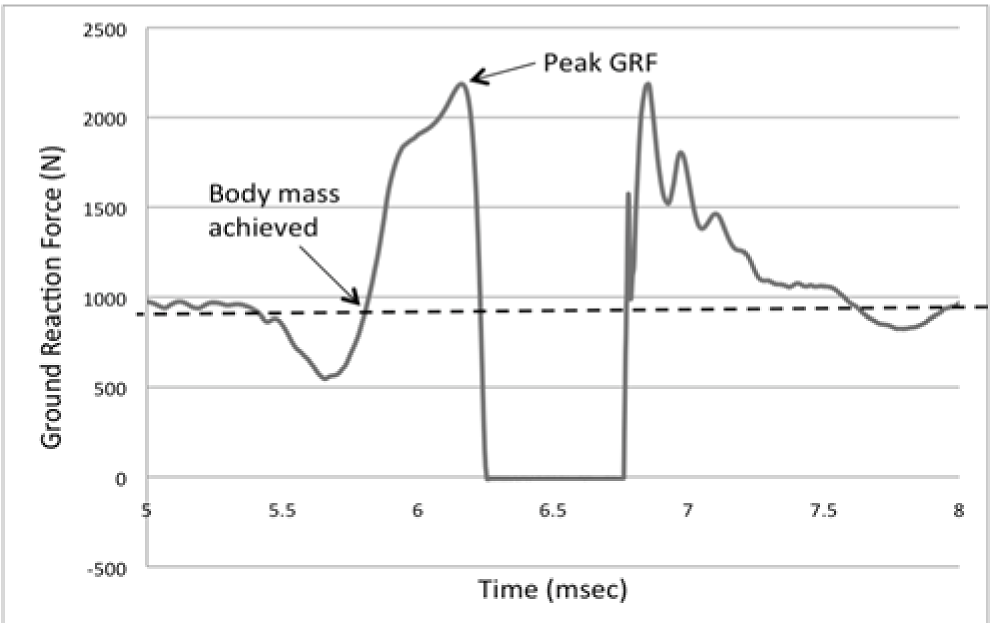

Figure 1: Graphical representation of acquired vertical ground reaction force traces and identified action points used to calculate rate of force development during a countermovement jump.

Statistical Analyses: All statistical analyses of the data were carried out in SPSS © (Version 15.0) using a significance level of 0.05. A One-way repeated measures ANOVA was used to determine differences in RFD100 (n = 23) and tGRF (n=16) across the

plyometric exercises. Pair-wise comparisons were performed using a Bonferroni's correction if significant differences were found for RFD100 and tGRF.
For RFD250 (n=23) the data was found to lack normality across the various jumps when significant skewness and kurtosis values were obtained for CH and TJ. Thus use of non-parametric statistics was required and a Friedman's ANOVA was used to compare the different jumps. If a significant difference was found for the RFD250 a Wilcoxon Signed Rank test was performed with Bonferroni's correction to determine where the differences occurred (Sheskin, 2007).

RESULTS AND DISCUSSION:
Analysis of the positive acceleration phase revealed significant differences ($p<0.05$) in RFD100 and tGRF between the plyometric exercises as shown in Table 1. As can be seen, plyometric exercises that had a lower RFD100 also had a longer time to peak GRF. Intuitively this makes sense, as a slower RFD would mean the individual must take more time to get to peak and to complete the acceleration phase of the movement. Of interest is that the CH and TJ, exercises which have the highest RFD100, took less than 250 msec to reach tGRF and obviously require quick movement. For the CH subjects jumped laterally over the cone as quickly as possible, while to complete the TJ subjects had to rapidly flex their hips and knees to touch the hands beneath the shank. As can be seen by the tGRF these plyometric exercises would be classified as the short component according to Schmidtbliecher (1992). On the other hand, exercises that place a large strength load on the muscle (SJ30 and SLJ) have a much lower RFD and longer tGRF and thus can be considered long component exercises (Schmidtbliecher, 1992). The SLJ requires a single leg to provide all the force and has been shown to have higher force relative to each leg (Jensen & Ebben, 2002; 2007). During the SJ30 the additional mass that must be moved requires greater force although it is distributed over both legs (Jensen & Ebben, 2002; 2007). According to Newton's Second Law to get a higher acceleration (RFD) the force must be higher (SLJ) or the mass lower (SJ30).

Table 1 Mean ± SD for Rate of Force Development 100 msec (n=23) and Time to Peak GRF (n=16) during various plyometric exercises.

	RFD100 ($N \cdot sec^{-1}$)	Time to Peak GRF (sec)
SLJ	4202.6 ± 3332.8 [a]	.398 ± .121 [a]
SJ30	4644.7 ± 3824.3 [a]	.454 ± .181 [a]
CMJ	7752.4 ± 3608.1 [b]	.286 ± .135
TJ	9682.0 ± 3468.7 [c]	.224 ± .072
CH	11331.5 ± 5164.5 [c]	.172 ± .058

[a] Significantly different from CMJ, TJ, CH ($p < 0.05$)
[b] Significantly different from SLJ, SJ30, TJ, CH ($p < 0.05$)
[c] Significantly different from SLJ, SJ30, CMJ ($p < 0.05$)

Friedman's ANOVA revealed that the SLJ and CH were ranked lowest for RFD250 while CMJ and TJ were ranked highest. The low RFD rankings for SLJ and CH were probably from opposite causes: CH because subjects had moved so quickly the GRF values were near or below zero; while SLJ was due to a very slow development of force in the tGRF. This is illustrated by examining Figure 1 where the SLJ would still be on the upward phase of the force trace, while the CH would be on the downward side, near zero.It should be noted that CH was often performed so quickly that several subjects had nearly left the force platform (ground) by the time the 250 msec was reached. Thus the values for RFD (determined by subtracting the GRF when body weight was achieved after the countermovement from the GRF at 250 msec) were often below zero as shown by the mean RFD250 (see Table 2). This would also indicate that classifying these types of exercises using fast or slow SSC (Schmidtbleicher, 1992), may be inappropriate due to difficulty in determining values for RFD250. In other words, using tGRF and perhaps RFD100 might be acceptable, but RFD250 would not.

Table 2 Mean ± SD and overall rank (1 being low) for Rate of Force Development 250 msec (n=23) during various plyometric exercises.

	RFD250 ($N \cdot sec^{-1}$)	Rank
SLJ	2475.9 ± 1296.9	2.00 [a]
CH	-12050.8 ± 59015.9	2.04 [a]
SJ30	3508.6 ± 1519.4	2.96 [b]
CMJ	4276.5 ± 1734.7	3.91
TJ	4073.3 ± 3499.8	4.09

[a] Significantly different from SJ30, CMJ, TJ ($p < 0.05$)
[b] Significantly different from CMJ, TJ ($p < 0.05$)

CONCLUSION:

In summary, SLJ and SJ30 had lower RFD100 and longer time to peak force, while CH and TJ had higher RFD100 and shorter time to peak force. These findings are in agreement with previous research that shows that some plyometric exercises, such as quick movement jumps, produce higher RFD while slower jumps have lower RFD. However, how long the RFD is measured may impact the findings. Thus RFD250 may be an inappropriate measure to classify very quick jumps, such as the CH, because RFD values approach zero or become negative when subjects are close to or already leaving the ground.

REFERENCES:

Aagaard P., Simonsen E.B., Andersen J.L., Magnusson P., and Dyhre-Poulsen P. (2002) Increased rate of force development and neural drive of human skeleton muscle following resistance training. *J Appl Physiol* 93: 1318-1326.
Bobbert, M.F., Gerritsen, K.G.M., Litjens, M.C.A., Van Soest, A.J.V. (1996) Why is countermovement jump height greater than squat jump height? *Med Sci Sport Exerc* 28: 1402-1412.
Ebben, W.P., Flanagan, E.P., Jensen, R.L. (2007) Gender similarities in rate of force development and time to takeoff during the countermovement jump. *J Exerc Physiology*online 10(6):10-17.
Flanagan, E.P. (2007) An examination of the slow and fast stretch shortening cycle in cross country runners and skiers. *Proc of the XXV International Symposium of Biomechanics in Sports*. 51-54.
Schmidtbleicher, D. (1992) Training for power events. In: Komi P.V. (ed) *Strength and Power in Sport.* Boston, MA: Blackwell Scientific, pp. 381-395.
Sheskin, D. (2007) *Handbook of Parametric and Nonparametric Statistical Procedures (4th Ed.)* Boca Raton, FL: Chapman and Hall/CRC 1075-1084.
Walshe, A.D., Wilson, G.J., Ettema, G.J.C. (1998) Stretch-shorten cycle compared with isometric preload: contributions to enhanced muscular performance. *J Appl Physiol.* 84, 97-106.
Wilson, G.J., Lyttle, A.D., Ostroski, K.J., Murphy, A.J. (1995) Assessing dynamic performance: A comparison of rate of force development tests. *J Strength Cond Res* 9: 176-181.

Acknowledgement
Sponsored in part by a Northern Michigan University Faculty Research Grant.