Lower Limb Power Output : A Literature Review

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Introduction

Variations on weight training, strength training, weight lifting, power lifting, speed training, plyometrics and combination training have been used by many coaches and athletes down the ages to improve performance. Even now, with the science and technology available to assess performance capabilities and training modes, there are still differences of opinion on which training mode is best suited for specific performance outcomes. It would be easy to suggest that the best option would be to employ all the above in a training programme to ensure that the athlete benefits from every aspect of strength, power and speed conditioning. However, this would not be appropriate and as such, it is important that coaches and athletes utilise the most effective methods of performance improvement for the specific individual development needs.

The purpose of this review is to compare any significant differences in the force, velocity and power output of lower limb muscles during countermovement jump (CMJ) and weighted squat (WS) type movements, and to assess how these should impact training prescription.

The Exercises

The squat, as previously described by Yule[40] and Chandler and Stone[8] is a widely recognised exercise that is used by athletes and recreational trainers to improve and increase a range of physical capacities. Almost every sport that requires the participant to use their legs in some way will probably use the squat, in one of its various forms, as part of a training routine to improve lower limb performance.

A CMJ is a plyometric type movement that utilises the stretch-shortening cycle, and is frequently used to develop a range of physical capacities including speed improvement.[6, 22, 38] It is performed from an upright stance with the feet shoulder width apart, and the hands either at the side of the body swinging or kept on the hips throughout the movement. The ankles, knees and hips are quickly flexed, then forcefully and quickly extended to achieve as much vertical height as possible. Various studies of the force, velocity and power outputs for CMJ have shown the benefits of using these exercises for the performance improvement of speed, strength and power, and are often used as part of a strength and conditioning programme.[11, 28]

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A Review of the Literature

The key to effective strength and conditioning is to improve sports performance. In many sports, running speed plays a major role, although it is the initial speed or acceleration, rather than the maximum speed that is seen as of greater importance for successful performance.[2, 11] This could be the initial acceleration needed to beat an opponent in a field sport such as rugby or hockey, or the reactive speed of movement required during racquet sports such as badminton or squash. In addressing improvement in sports performance such as acceleration, it has been suggested that measures of athletic performance are strongly correlated with measures of maximum force, the rate of force development and power.[33] This makes a comparison of methods aimed to enhance these qualities very important.

The basis for this literature review is derived from several independent studies looking at squats and various jumps and their force and power outputs determined from force platform data and jump heights.[2, 4, 6, 10, 14, 16, 37] From these studies, it is apparent that the rate of force development (RFD), is a key component in achieving quick movement. RFD has historically been calculated during an isometric contraction performed on a dynamometer; however, recent studies have shown that the RFD for dynamic movement on a force platform can be calculated using force, velocity and time data.[27, 33] This applied approach to testing can therefore utilise exercises that are used in the field, and are thus more applicable to sporting performance.

Power = velocity x force, and therefore has both a force and a velocity component. Having a high proportion of fast twitch or type II muscle fibres is important for high force, high velocity and high power outputs. It is understood that the amount of force that can be developed has a significant impact on power production. The velocity at which that force can be utilised for sport performance often determines the level of success or the outcome of the performance, as was shown by Farina[15] and his colleagues, where it was suggested that larger numbers of fast twitch or type II motor units are recruited at faster limb speeds with respect to slower limb speeds, even at similar external forces. Hence, the ability to generate power could be one of the most important factors in sports performance, particularly in those sports involving sprinting, change of direction and jumping.[20] It must be recognised and understood that these three elements of dynamic performance i.e. speed, strength and power, require different training strategies and stimulus to achieve their potential.

An increase in strength or force production generally coincides with an increase in one, some or all of the following; muscle cross-sectional area (muscle hypertrophy), an increased proportion of fast type IIa phenotypes and myosin heavy chain (MHC) isoforms, greater pennation angles, greater neural drive, increased RFD, increased motor unit (MU) firing rates and synchronisation.[1, 3, 12, 37] It is accepted that increases in force production can increase power outputs, however if strength was the only prerequisite for speed then the power lifting champions would also be 100m sprint champions, and this is not the case. Absolute peak force is therefore not the only factor that should be considered when looking at speed of movement. The time to peak force or the amount of force that can be developed in the early phase ($\leq$250 ms) of muscle contraction is also important to sport performance. It has been shown that dynamic, explosive or maximal velocity training can increase the RFD, thus reducing the time to peak force or increasing force production earlier in the contraction.[12, 41]

Typical contraction times to maximum force for large limb muscles are $\geq$300 ms, however, sports such as sprinting, boxing and some athletic field events involve contraction times of 50-250 ms[1], which implies that peak force is not achieved during these actions. Maximal force contractions are only required for a few sports such as powerlifting. Most sports require force at higher movement velocities.[35]

A study of propulsion forces involved during weightlifting and CMJ indicated that performance was not improved by increasing the magnitude of force generation, but by increasing the rate of force generation and the time during which a higher percentage of maximum force is applied.[19] Therefore, if more force can be developed more quickly, resulting in a leftward shift of the force/time curve, i.e. the RFD, during the early phase (100-200 ms) of muscle contraction, then this would enhance power output and consequently sport performance.[1, 27]

It is accepted that weightlifting, i.e. the clean and jerk and the snatch, where athletes attempt to lift the most weight, as opposed to weight or resistance training,[9] is recognised as having among the highest power outputs for human movement. For example, a 1 repetition maximum (1RM) lift in the snatch can produce a maximum power output of 3000 Watts (W), in comparison to 1100 W by the same lifter for a 1RM lift in a squat,[27, 28] whilst a recording of 6981 W was made during the second pull of a world record attempt at the clean.[18]

However, it has been suggested that the optimal training load for power development is approximately 30% of the 1RM[27, 28, 39], although optimal loads of between 10 and 85% have also been suggested[27, 28] and that the highest power output and RFD is found in those athletes who combine high force and high velocity training.[20]

It has also been demonstrated that average and peak force and velocity are higher during ballistic movements, (where the load is released at the end of the range of motion) than traditional lifts, due to the deceleration required to stop the load at the end of the conventional movement.[29] Kellis' study reported that as the load during the squat was reduced, then the deceleration phase increased thus reducing all force and kinematic parameters. However, the GRF was maintained at near maximal levels throughout loaded squat jumps and peak GRF was recorded in the early phase of the movement.[29]

Recent studies have also suggested that the highest instantaneous peak power may be achieved at bodyweight i.e. no external load.[14, 37] Garhammer[18] reported that the power outputs for the CMJ of experienced weightlifters came within ± 10% of the power outputs for the second pull phase of a snatch or clean, approximately 5000W, (see *Table 1*). This is interesting from an applied perspective, in that taking a simple measure of CMJ height will allow for quick and easy monitoring of power gains during an S&C training phase. Studies have shown that heavy resistance training, at loads of 80-90% 1RM can improve force output and the rate at which that force is applied.[1, 21] However, velocity specific or high velocity training at loads of 30% 1RM and less have also been shown to improve power output and RFD.[12, 27, 28] It should be noted however, that these studies have used a variety of testing methods, tools, protocols and subjects, and as such it would not be possible or appropriate to directly compare the results.

Table 1. Means (s.d.) for squat and CMJ and comparative data from related studies.

Sub			Total time	Pmax	Vmax	Fmax	pRFD	Av. RMS
Squat mean			1.14	438.2	0.2125	1129.33	3812.6	0.093
Squat stdev			0.31	563.02	0.20	360.52	2328.64	0.03
CMJ mean			0.68	3656.18	3.988	1105.67	4282.96	0.024
CMJ stdev			0.18	1205.25	1.35	138.84	1092.29	0.02
Comparative data								
Ref. 1	Clean second pull		0.12	6981				
Ref. 1	Squat		2	1200	0.6			
Ref. 1	Clean pull & Snatch			3430				
Ref. 1	Second pull			5260				
Ref. 2	Jerk		0.32*	5400	2.6*			
Ref. 2	Snatch			3000	2.0*(pull)			
Ref. 2	Clean		0.98*	2950	1.6*			
Ref. 2	Squat			1100				
Ref. 3	CMJ			5023	2.8	2228		
Ref. 4	Squat jump			4320	2.46	1374		

** data relevant to the adjacent exercise but taken from reference 1.*

Ref. 1. (Garhammer, 1993).[18]

Ref. 2. (Haff & Potteiger, 2001).[20]

Ref. 3. (Izquierdo et al. 1998).[24]

Ref. 4. (Driss et al. 2001).[14]

Non referenced data from an Honours Degree dissertation 2006.

As previously discussed, there are various suggestions for the optimal load for power development, although many of these studies neglected to report or test the power outputs at body weight or 0% 1RM for lower limb movements. Only 2 studies have been found that test or extrapolate lower limb power output at 0% external loading, although the studies used different subject populations and testing protocols.[14, 37] However in both studies, a squat jump was used in comparison to a loaded squat jump or squat, and both studies demonstrated that the unloaded squat jump produced the highest power output.

There are several possible reasons as to why CMJ height is greater than squat jump height and thus potentially, a more powerful movement. A counter-movement utilises the stretch-shortening cycle (SSC), which is an eccentric contraction or stretch under load followed immediately by a concentric contraction, which allows for higher forces to be developed in the muscle tendon unit at the start of the concentric contraction and so to an increase in its force development capabilities.[22, 23, 38]

There are several mechanisms thought to be responsible for this, either singularly or in combination. One hypothesis for the greater performance of the CMJ is that a higher level of active muscle state is achieved prior to the onset of the concentric contraction; in that there is greater cross-bridge attachment and less myofibrillar displacement than in a standard squat jump. In this way, concentric contraction commences at a more optimum length, enabling greater joint movements.[6, 38] It has also been suggested that the storage and reutilisation of elastic energy may improve performance with a countermovement, by storing energy gained during the active pre-stretch in the series elastic elements for use during the concentric phase, which theoretically improves the work accomplished.[6]

It has been demonstrated that pre-stretching, or the potentiation of the contractile element, alters the muscle fibre properties, improving the mechanical work of the muscles during the first 300 ms of shortening. It is important to note that the velocity and displacement of the pre-stretch significantly affects the level of force that can be produced.[6, 38] It has been suggested that the CMJ has a higher peak power output than a WS in studies by Garhammer[18], for the squat 1274 W, by Haff and Potteiger[20] for the squat 1100 W, by McBride[31] for the CMJ 4910 W, and by Izquierdo *et al*[24] for the CMJ 5023 W. However, these studies mostly use trained athletes, power lifters and weight lifters.[16, 18, 20, 31]

The greater vertical velocity logically begets a lesser time for the concentric contraction for the same range of motion. A greater vertical velocity for the CMJ, but with a similar GRF to the WS would imply a more powerful contraction was produced during the CMJ. It has been suggested that elite weight lifters can produce similar power outputs for CMJ and the second pull of a snatch or clean. Interestingly the time taken to complete the second pull of these lifts has been reported as 0.12 s, while for the jerk phase of a clean and jerk, the time has been reported as 0.32 s, which indicates that velocity is a significant component of human muscle power output.[18]

As previously discussed muscle contraction times during most sports do not allow peak force to be attained. It is therefore surmised that if the rate at which force can be developed, and the amount of force that can be developed earlier in the contraction can be increased, then the greater the power output. This indicates a shift to the left of the force/time curve and represents an increase in the RFD, if not a difference in the pRFD.

It is thought by many coaches and athletes that to increase power, heavy weights must be lifted, which would result in an increase in force development. This is correct in that power is a product of both force and velocity and an increase in one or the other will result in an increase in power. Although studies have given force outputs for the squat as 2413 N by Fatouros *et al*[16], and as 2381 N by Kellis *et al*,[29] in comparison to force outputs for the CMJ of 2228 N by Izquierdo *et al*[24], and of 1934 N by McBride *et al*.[31]

Increases in stretching speeds during the SSC are strongly associated with increases in force outputs during jumping motions.[7, 30] Therefore, the use of CMJ and depth/drop jumps, (where the subject jumps from a given height to the floor to perform a CMJ type movement), would elicit maximal force generation in the shortest period of time and consequently an increase in power output. Studies on combination/complex training suggest that performing a plyometric type exercise after a heavy resistance exercise could be beneficial due to the heightened stimulation of the neuromuscular system, potentially creating optimal conditions for the subsequent plyometric exercise.[25, 26]

This phenomenon of post-activation potentiation during combination/complex training may induce a similar neuromuscular response as the pre-stretch occurring during the SSC of plyometric movements. The faster the eccentric or countermovement phase of a CMJ, then the greater the potentiation effect and the more powerful the concentric contraction.[7, 30] This could suggest a further reduction in the number of exercises needed to be performed during a training schedule, thus increasing efficiency and reducing the risk of overtraining. Further benefits of plyometric training have been reported to include increased motor unit functioning, increased inhibition of antagonist muscles as well as improved activation and co-contraction of synergistic muscles, and increased muscle stiffness.[7, 30]

It would therefore seem that increasing the use of, or including plyometric exercises within a periodised plan will have both performance improvement and potentially organisational benefits.

Conclusions and recommendations

In conclusion, this review suggests that plyometric type movements have a higher peak power output than squat type or non ballistic movements. Interestingly, there was little difference in force outputs or peak RFD between the two types of exercise. This runs in contrary to some suggestions that there would be differences in these variables between the two conditions. The time to peak RFD, total concentric contraction time and vertical velocities all concur to suggest that plyometric and ballistic type movements are more powerful than non ballistic movements.

This evidence gives further weight to the inclusion of high velocity training in an S&C programme, as well as training with high loads for athletes involved in sports where speed of movement is important. Future studies should consider whether depth/drop jumps elicit higher peak and/or average power outputs than CMJ, and if post-activation potentiation has a significantly greater effect on the subsequent concentric contraction than pre-stretch potentiation.

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