EFFECTS OF ECCENTRIC AND CONCENTRIC STRENGTH TRAINING ON MAXIMUM STRENGTH, POWER VARIABLES AND DYNAMIC STRENGTH INDEX

Ville Rajalainen

Science of Sport Coaching and Fitness Testing
Master's thesis
Faculty of Sport and Health Sciences
University of Jyväskylä
Spring 2021

ABSTRACT

Rajalainen, V. 2021. Effects of eccentric and concentric strength training on maximum strength, power variables and dynamic strength index. Faculty of Sport and Health Sciences, University of Jyväskylä, Master's thesis in Science of Sport Coaching and Fitness Testing. 54pp.

Eccentric and concentric strength training have been studied and compared since 1890's. Studies have reported mixing results regarding strength gains. Also, research focusing on the effects of these training modalities on variables of power output is scarce. Dynamic Strength Index (DSI) has been proposed to be an effective tool of assessing athlete's strength qualities to direct future strength training optimally. DSI is described as peak force in dynamic movement divided by peak force in the subsequent isometric effort. Few studies have examined the effects of strength training on DSI, and no previous studies have compared the effects of concentric and eccentric strength training protocols. This study aimed to compare the effects of eccentric and concentric strength training on maximum strength, DSI, and maximal power output in untrained or recreationally trained adults.

A total of 46 participants, including both men and women, completed the training intervention with maximal isolated isokinetic concentric or eccentric bench press exercises with a custom-made bench press device. Participants were divided in to concentric (CON, n=24, 30.0 ± 4.1 years, 1.73 ± 0.10 m, 72.0 ± 11.3 kg, 23.8 ± 2.7 BMI) and eccentric (ECC, n=22, 27.7 ± 5.2 years, 1.73 ± 0.07 m, 74.1 ± 10.5 kg, 24.7 ± 3.2 BMI) training groups with similar 1RM in dynamic bench press at baseline (p=0.94). Both groups trained twice per week for 10 weeks with PRE measurements at week 1, MID measurements at week 6, and POST measurements at week 10. 1RM test, isometric bench press, and bench press throw (BPT) with loads of 30%, 45%, and 60% of 1RM were performed at each testing session. Peak force in the isometric bench press and BPT were used to calculate DSI.

No differences between the training methods were observed in 1RM, DSI, isometric bench press or BPT related variables. 1RM increased in both concentric and eccentric training groups from 57.6 ± 20.2kg to 59.3 ± 19.9kg and 56.7 ± 19.4kg to 61.1 ± 20.2kg PRE to MID, respectively ($p<0.001$). Both CON and ECC training groups increased their 1RM to 64.0 ± 21.3kg and 63.9 ± 19.9kg MID to POST, respectively ($p<0.001$). Peak force in isometric bench press increased from PRE to POST ($p<0.05$) and from MID to POST in both groups (ECC: 613.3 ± 190.4N to 659.1 ± 190.8N, $p<0.001$; CON: 599.0 ± 198.2N to 636.8 ± 209.9N, $p<0.05$). Peak force in BPT increased only in CON group with 60% 1RM load from PRE to POST (ECC: 153.7 ± 62.8 to 149.5 ± 60.7N; CON: 149.5 ± 59.3 to 171.0 ± 71.8N, $p<0.05$). Both groups increased their peak power from PRE to POST condition with all loads (30%1RM; ECC: 527.9 ± 178.4W to 548.4 ± 207.9W; CON: 490.1 ± 202.1W to 540.2 ± 178.4W, 45%1RM; ECC: 479.8 ± 190.7W to 552.5 ± 211.6W; CON: 447.5 ± 203.7W to 493.7 ± 179.3W; 60%1RM; ECC: 448.0 ± 164.7W to 497.8 ± 178.6W; CON: 412.3 ± 138.5W to 448.7 ± 143.3W).

The present study showed that maximal isokinetic eccentric and concentric bench press strength training for 10 weeks induced similar changes in bench press 1RM, isometric peak force, and BPT performance. No changes in DSI were observed, although isometric peak force increased in both groups.

Key words: bench press exercise, isometric bench press, bench press throw, isokinetic strength training

TIIVISTELMÄ

Rajalainen, V. 2021. Eksentrisen ja konsentrisen voimaharjoittelun vaikutukset maksimivoimaan, tehomuuttujiin ja dynaamiseen voimaindeksiin. Liikuntatieteellinen tiedekunta, Jyväskylän yliopisto. Valmennus- ja Testausoppi, Pro Gradu -tutkielma. 54 sivua.

Eksentristä ja konsentrista voimaharjoittelua on tutkittu ja vertailtu jo 1890-luvulta alkaen. Kirjallisuudessa on raportoitu ristiriitaisia tuloksia näiden harjoitustyyppien vaikutuksesta voimaan. Eksentrisen ja konsentrisen harjoittelun vaikutuksia tehontuottoon on tutkittu vähän. Dynaaminen voimaindeksi (DSI) on laskennallinen tapa urheilijan voimaominaisuuksien arvioimiseen ja voimaharjoittelun suunnittelun tueksi. DSI määritellään dynaamisen liikkeen huippuvoiman ja vastaavan isometrisen suorituksen huippuvoiman suhteena. Vain vähän tutkimuksia on tehty voimaharjoittelun vaikutuksista dynaamiseen voimavajeeseen ja aiemmat tutkimukset eivät ole verranneet eksentrisen ja konsentrisen voimaharjoittelun vaikutuksia dynaamiseen voimavajeeseen. Tämän tutkimuksen tavoitteena oli selvittää eroavatko eksentrisen ja konsentrisen voimaharjoittelun adaptaatiot dynaamisessa voimavajeessa tai maksimaalisessa tehontuotossa harjoittelemattomilla ja voimaharjoittelua harrastaneilla.

Yhteensä 46 tutkittavaa suorittivat harjoitusintervention. Tutkittavien joukossa oli sekä miehiä, että naisia. Interventiossa suoritettiin eristettyjä konsentrisia tai eksentrisiä suorituksia kustomoidussa isokineettisessä penkkipunnerrus laitteessa. Tutkittavat jaettiin konsentriseen (CON, n=24, 30.0 ± 4.1 vuotta, 1.73 ± 0.10 m, 72.0 ± 11.3 kg, 23.8 ± 2.7 BMI) ja eksentriseen (ECC, n=22, 27.7 ± 5.2 vuotta, 1.73 ± 0.07 m, 74.1 ± 10.5 kg, 24.7 ± 3.2 BMI) harjoitusryhmään siten, että yhden toiston maksimi (1RM) ei eronnut merkittävästi ($p=0.94$). Molemmat ryhmät harjoittelivat kahdesti viikossa 10 viikon ajan. Alkumittaukset (PRE) suoritettiin viikolla 1, välimittaukset (MID) suoritettiin viikolla 6 ja loppumittaukset (POST) suoritettiin viikolla 10. Jokaisella mittauskerralla mitattiin tutkittavien 1RM, isometrisen penkkipunnerruksen huippuvoima, sekä penkkipunnerrusheitossa (BPT) huippuvoima, huipputeho ja impulssi 30%, 45% ja 60% 1RM kuormilla. Huippuvoima isometrisessä penkkipunnerruksessa ja penkkipunnerrusheitossa käytettiin DSI:n laskemiseen.

Ryhmien välillä ei havaittu merkittäviä eroja 1RM tuloksissa, DSI:ssä, isometrisen penkkipunnerruksen huippuvoimassa tai BPT muuttujissa. 1RM kasvoi sekä CON, että ECC ryhmässä alkumittauksista loppumittauksiin (CON: PRE 57.6 ± 20.2kg ja MID 59.3 ± 19.9kg ja ECC: PRE 56.7 ± 19.4kg, MID: 61.1 ± 20.2kg) ($p<0.001$). 1RM tulos kehittyi molemmissa ryhmissä myös välimittauksista loppumittauksiin (POST: CON 64.0 ± 21.3kg ja ECC 63.9 ± 19.9kg) ($p<0.001$). Isometrisen penkkipunnerruksen huippuvoima kasvoi alkumittauksista loppumittauksiin ($p<0.05$) ja välimittauksista loppumittauksiin molemmissa ryhmissä (ECC: 613.3 ± 190.4N:sta 659.1 ± 190.8N:iin, $p<0.001$; CON: 599.0±198.2N:sta 636.8± 209.9N:iin, $p<0.05$). Huippuvoima penkkipunnerrusheitoissa kasvoi vain konsentrisesti harjoitelleella ryhmällä ja 60%1RM kuormalla (ECC: 153.7 ± 62.8 to 149.5 ± 60.7N; CON: 149.5 ± 59.3 to 171.0 ± 71.8N, $p<0.05$). Huipputeho penkkipunnerrusheitossa sen sijaan kasvoi molemmilla ryhmillä ja kaikilla kuormilla. (30%1RM; ECC: 527.9 ± 178.4W:sta 548.4 ± 207.9W:iin; CON: 490.1 ± 202.1W:sta to 540.2 ± 178.4W:iin, 45%1RM; ECC: 479.8 ± 190.7W:sta 552.5 ± 211.6W:iin; CON: 447.5 ± 203.7W:sta 493.7 ± 179.3W:iin; 60%1RM; ECC: 448.0 ± 164.7W:sta 497.8 ± 178.6W:iin; CON: 412.3 ± 138.5W:sta 448.7 ± 143.3W:iin).

Tämä tutkimus osoitti, että isokineettisellä eksentrisellä ja konsentrisella 10 viikon voimaharjoittelulla oli samansuuntaiset vaikutukset jälkeen penkkipunnerruksen yhden toiston maksimiin, isometrisen penkkipunnerruksen huippuvoimaan ja huippuvoimaan penkkipunnerrusheitossa. DSI ei muuttunut harjoitusjakson aikana, vaikka isometrisessä huippuvoima kasvoi molemmilla ryhmillä.

Asiasanat: penkkipunnerrus, isometrinen penkkipunnerrus, penkkipunnerrusheitto, isokineettinen voimaharjoittelu

ACKNOWLEDGEMENTS

I would like to thank each participant for taking part in the study. Fellow students writing your master’s or bachelor’s thesis in this project: thank you for your support and time. Thank you for all of our research trainees. This thesis was part of an international research project. Thank you for my supervisor Juha Ahtiainen, project leader prof. Keijo Häkkinen and everyone else at University of Jyväskylä who participated in making this project run.

LIST OF ABBREVIATIONS

%CV - percent coefficient of variation

1RM - one repetition maximum

3RM - three repetitions maximum

BP - bench press

BPT - bench press throw

BP-DSI - bench press derived dynamic strength index

CMJ - counter-movement jump

CMJ-DSI - counter-movement jump derived dynamic strength index

CON - concentric training group

CONT - control measurement

CSA - cross-sectional area

DSI - dynamic strength index

ECC - eccentric training group

EMG - electromyography

FL - fascicle length

GM - m. gastrocnemius medialis

ICC - intra-class correlation

IMTP - isometric mid-thigh pull

MHC - myosin heavy chain

MID - mid-training measurement

MVC - maximal voluntary contraction

PA - pennation angle

POST - post training intervention measurement

POST2 - post detraining measurement

PRE - measurement at the onset of training intervention

PRFD - peak rate of force development

RFD - rate of force development

SD - standard deviation

SJ - squat jump

SJ-DSI - squat jump deriver dynamic strength index

TE - typical error

VL - m. vastus lateralis

TABLE OF CONTENT

ABSTRACT

1 INTRODUCTION 1

2 MUSCLE POWER PRODUCTION.. 3

  2.1 Effects of fiber type on muscle power production 4

  2.2 Effects of muscle arcitechture on power production... 5

  2.3 Effects of neural drive on muscle power production 6

3 ECCENTRIC VS CONCENTRIC STRENGTH TRAINING 8

  3.1 Hypertrophy 9

  3.2 Fiber type composition and muscle architecture 11

  3.3 Neural control.. 13

  3.4 Strength 14

  3.5 Power.. 15

4 DYNAMIC STRENGTH INDEX 17

  4.1 Determinants of DSI.. 17

  4.2 Reliability of DSI 18

  4.3 Reference values of DSI presented in literature 19

  4.4 Effects of strength training on DSI 20

  4.5 Directing training interventions based on DSI 22

5 RESEARCH QUESTIONS & HYPOTHESES 24

6 METHODS 26

  6.1 Participants 26

  6.2 Study design 27

  6.3 Training protocol.. 28

  6.4 Measurement protocol.. 31

  6.5 Data analysis 34

  6.6 Statistical analysis 34

7 RESULTS 35
7.1 1RM bench press 35
7.2 Impulse in BPT 35
7.3 Peak force in BPT 37
7.4 Peak power in BPT 37
7.5 Isometric peak force 39
7.6 Dynamic Strength Index 39
8 DISCUSSION 41
8.1 One repetition maximum (1RM) 41
8.2 Peak Force in BPT 41
8.3 Isometric Peak Force 42
8.4 Peak power in BPT 43
8.5 Impulse in BPT 43
8.6 Dynamic strength index 44
8.7 Strengths and limitations of the present study 45
8.8 Conclusion 45
8.9 Practical applications 46
REFERENCES 47

1 INTRODUCTION

Power production of muscles is dictated by the force-velocity relationship. When assuming standardized neural command, this relationship is distorted by morphological characteristics of the muscle, such as muscle fiber type, fascicle length and pennation angle. *In vivo* muscle power production is more complex with varying states of motor unit recruitment, firing frequency and antagonist co-activation. (Cormie et al. 2011a.)

Eccentric and concentric contraction types of the muscles have been studied since the 1890's (Blix, 1892; according to Mannheimer, 1968). It is known that eccentric contractions produce higher force than concentric or isometric contractions (Abbott et al. 1952) and that magnitude of difference can be up to 45% (Jones & Rutheford, 1987). Albeit producing higher forces, velocity matched eccentric concentrations require lower neural control than their concentric counterparts measured as lower EMG activity (Westing et al. 1991). It has been suggested, that eccentric contractions might lead to higher gains in muscle volume and strength due to higher mechanical stress (Schoenfeld et al. 2017). There is some evidence for eccentric contractions to produce increased hypertrophic responses (Higbie et al. 1996; Seger et al. 1998; Hawkins et al. 1999; Hortobagyi et al. 2000; Farthing et al. 2003 & Vikne et al. 2006), but a meta-analysis by Schoenfeld et al. (2017) did not result in significant differences between the muscle action types. Similarly, equivocal results have been observed regarding muscle strength.

Research on concentric and eccentric strength training has focused on markers of muscle strength and muscle volume and rather limited studies have been conducted on how eccentric and concentric strength training affects muscular power. Some evidence shows increased jumping performance after eccentric cycling compared to concentric cycling (Gross et al. 2010; Elmer et al. 2012).

Dynamic strength index (DSI) or dynamic strength deficit (DSD) is a tool to assess individual strength and power qualities and to profile athlete's training needs (Sheppard et al. 2011; Young et al. 2015; Thomas et al. 2015). DSI is expressed as the ratio of dynamic movement peak force to subsequent isometric peak force. Mixed results on how strength training affects

DSI have been reported (Young et al. 2015; Comfort et al. 2018b). To my knowledge, no studies comparing effects of eccentric and concentric strength training on DSI have been conducted.

In the current study participants were asked to perform strength training using maximal effort isokinetic eccentric or isokinetic concentric bench press for 10 weeks. Effects of both training modalities on bench press throw (BPT) performance, isometric BP and DSI were measured. The aim of this study was to examine if eccentric and concentric strength training elicit different changes in DSI, isometric peak force, 1RM and maximal power output in BPT.

2 MUSCLE POWER PRODUCTION

Muscle power is determined by the load-velocity relationship (also referred as force-velocity relationship), which dictates that higher movement speed results to lower forces. When reversed, this means that higher forces are harder to be generated in a short amount of time. This is due the specific time of action-myosin bonds require to attach and detach, and when the time is constrained, force production of the muscle is similarly constrained. Thus, power is maximized at sub-maximal velocity and force values (figure 1). Theoretically increasing one's maximal power can be achieved by increasing maximal force, maximal velocity or decreasing the curvature of the curve. (Cormie et al. 2011a). High correlation between maximal strength and maximal power is indeed well established in elbow flexors (figure 2) (Moss et al. 1997).

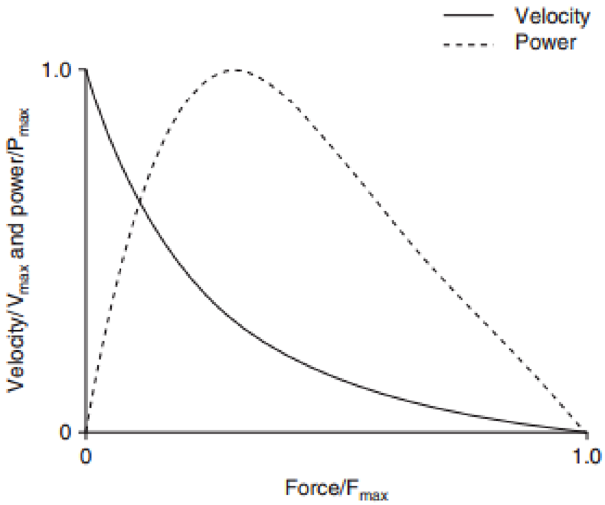


FIGURE 1. Force-velocity relationship of the muscles. (Cormie et al. 2011a).

Interestingly, 1RM result was not correlated to power output in concentric only movements. In eccentric-concentric movements correlation was significant, but these results may reflect the fact that 1RM BP was measured via eccentric-concentric BP exercise. (Cronin et al. 2000).

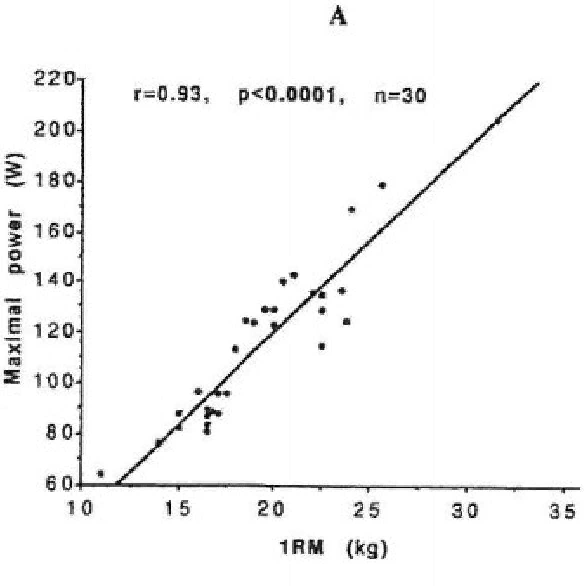


FIGURE 2. Maximal power correlates well with 1RM in elbow flexors. (Moss et al. 1997)

In bench press exercise, Bartholomei et al. (2018) reported high correlation (r=0.87, p<0.001) between 1RM bench press and bench press throw maximum mean power. There is some evidence, that the greatest power output in BP is achieved with a relative load of 30% 1RM (Bevan et al. 2010), but the value depends on the training status and sex of the subjects (Miller et al. 2019). In the study by Miller et al. (2019) previously trained and untrained men and women performed BP exercise. Trained men reached similar results as Bevan et al. (2010) with men producing highest peak power with 30-40% 1RM loads, but untrained men produced peak power with 60-70% 1RM. Comparison between sexes revealed that trained women produced peak power with higher relative loads than trained men, with 50% 1RM. Untrained women reached their peak force with similar relative loads as untrained men, with 60-70% 1RM. (Miller et al. 2019).

2.1 Effects of fiber type on muscle power production

The force-velocity realtionship is distorted if single muscle fibers are examined with type II fibers showing a higher power output per CSA (cross-sectional area) compared to type I fibers (Cormie et al. 2011a). It is reported that in human body temperature of 37 degrees Celcius type

II fiber bundles have 3-fold maximal contractile velocity and 4-fold maximal power output compared with type I fiber bundles (Faulkner et al. in Jones et al. 1986, 81-94; according to Cormie et al. 2011a) Other studies have reached similar results of hihger specific force in type II fibers over type I fibers, but most of these studies don't reflect *in vivo* examples as measurement temperatures do not reflect body temperature (Cormie et al. 2011a).

As an extreme example, Plas et al. (2015) reported marmoset (*Callithrix jacchus*) to have about twice as high body or leg muscle mass-specific mean power output during vertical jump push-off. They determined this was at least partly due to marmoset *vastus lateralis* (VL) and *gastrognemius medialis* (GM) muscles consisting of high precentage of type IIb myosin heavy chains (MHC) (VL; 68.9±5.1% in the distal part and 56.5±7.50% in the proximal part, GM; 48.0±4.5% in the distal part and 40.6±12.37% in the proximal part). In addition, slow contracting type I myosin heavy chains were expressed in small protions for both muscles in marmosets, with notably higher values of type I myosin heavy chains reported in human muscle fibers (Green et al. 1981; Plas et al. 2015).

2.2 Effects of muscle arcitechture on power production

Muscle CSA and fiber CSA. Regardless of the fiber type, muscle fiber CSA affects the maximal force able to be generated by the fiber (Cormie et al. 2011a). It is reported, that there is a strong and significant positive correlation between muscle CSA and muscle force (Ikegawa et al. 2008) and power (figure 3) (Moss et al., 1997). Study by Maughan et al. (1984) reported force-to-CSA ratio to be similar in strength trained and untrained subjects, but Ikigawa et al. (2008) showed force to CSA ratio to be significantly different in bodybuilders and weightlifters, weigthlifters showing significantly higher force-to-CSA ratio. Akagi et al. (2014) reported strong correlation between bench press throw peak power and *pectoralis major* muscle volume.

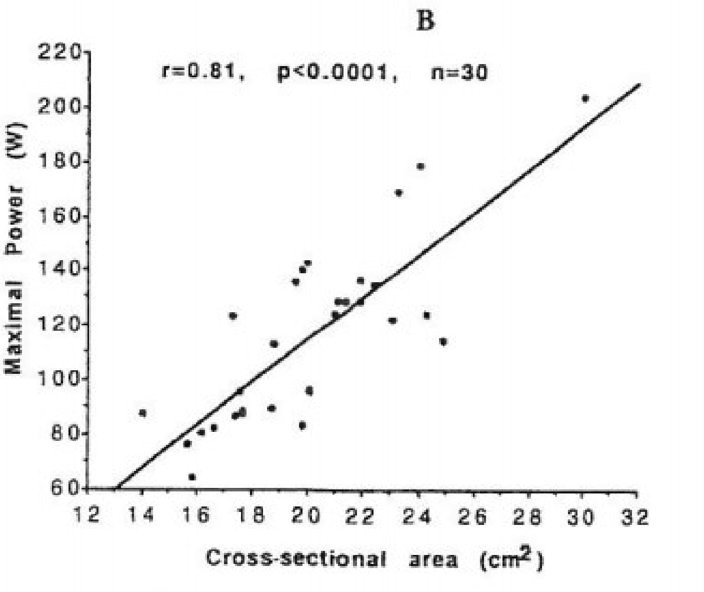


FIGURE 3. Maximal power correlates well with muscle cross-sectional area. (Moss et al. 1997).

Fasicle length. Longer muscle fascicles result to higher muscle contracting velocities (Lieber & Ward, 2011) and they are able to generate higher forces in settings of high shortening velocity (Blazevich, 2006). Since muscle contracting velocity and force are main determinants of muscle power, longer fascicle length (FL) results in higher peak power and decreased curvature of force-velocity relationship (Cormie et al. 2011a).

Pennation angle. Larger pennation angle (PA) is associated with lower force relative to muscle CSA ratio in strength-trained athletes (Ikegawa et al. 2008). This is supported by results from Strasser et al. (2013), who reported PA to have an inverted correlation with maximal voluntary contraction (MVC) force. Since force is a main determinant of muscle power production, smaller PA results in increased power output.

2.3 Effects of neural drive on muscle power production

Measured as the electrical activity of the agonist muscle(s), neural drive affects muscle power production. Neural drive on the muscle level consists of motor unit recruitment and firing frequenzy. The net force produced by the agonist muscle is also affected by the force generated by anatagoinst muscle activation.

Motor unit recruitment. Motor units are recruited in according the size principle starting from small α-motoneurons innervating type I motorunits towards larger α-motoneurons innervating type II fibers (Henneman et al. 1965; according to Cormie et al. 2011a). Recruiting larger and more force producing motor units earlier would be a positive outcome for power production (Cormie et al. 2011a). Motor unit recruitment can be studied using interpolated twitch technique. Such studies report that effects of strength training on motor unit requirement is unclear (Shield & Zhou, 2004). In bench press exercise all the motor units are activated after 80% 1RM load with no further motor units recruited at 90% 1RM (Pinto et al.2013).

Firing frequency. Firing frequency is described as the rate of actionpotentials transmitted from the motoneurons to muscle fibers. This can enhance muscle rate of force development (RFD) and thus muscle power production in short timeframes. (Cormie et al. 2011a).

Antagonist muscle co-activation. Activation of the antagonist muscles reduces the net force produced by agonist muscles. Co-activation is higher a) when movement is performed with higher loads, b) in women than men and c) during concentric actions over eccentric actions (Pincivero et al. 2019). Reducing antagonist co-activation is beneficial for voluntary force and power production.

3 ECCENTRIC VS CONCENTRIC STRENGTH TRAINING

Eccentric and concentric contraction types of the muscles have been studied since the 1890's (Blix, 1892 according to Mannheimer, 1968). It is known that eccentric contractions produce higher force than concentric or isometric contractions (Abbott et al. 1952, Doss et al. 1965) and that magnitude of difference can be up to 45% in isokinetic setting (Jones & Rutheford, 1987). For bench press exercise, Holliander et al. (2007) reported eccentric force to be 40% higher than concentric force for men and 146% for women. Albeit producing higher forces, velocity matched eccentric concentrations require lower neural control than their concentric counterparts measured as lower EMG activity (Westing et al. 1991). Since eccentric contractions produce higher forces, it has been suggested that eccentric strength training would elicit higher strength gains due to higher mechanical loading (Doss et al. 1965).

The underlying problem of studying effects of isokinetic concentric and eccentric strength training is that maximal effort repetitions lead to higher forces in the eccentric setting, if not taken in to account in the study design (Abbott et al. 1952). Some studies have accounted for this by prescribing higher intensities for eccentric group, as Raue et al. (2005) have done (figure 4).

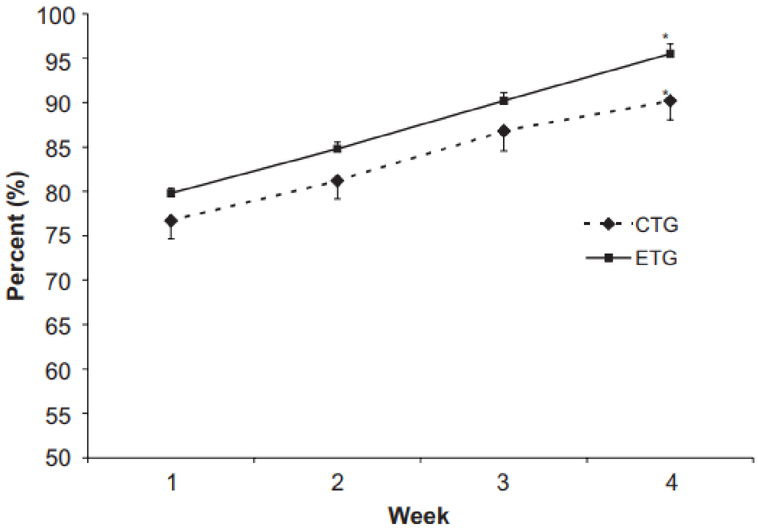


FIGURE 4. Training intensity as % of concentric 1RM. Eccentric training group was prescribed with higher training intensities throughout the training program (Raue et al. 2005).

3.1 Hypertrophy

Body of evidence promotes the assumption that eccentric training is more beneficial for muscle hypertrophy and eccentric training generates significant results in muscle CSA (Higbie et al. 1996; Seger et al. 1998; Vikne et al. 2006; Roig et al. 2008), muscle thickness (Farthing et al. 2003), lean mass (Hawkins et al. 1999), muscle girth (Roig et al. 2008) or fiber CSA (Hortobagyi et al. 2000; Vikne et al. 2006) compared to concentric training. In support for these results, Moore et al. (2005) reported higher myofibrillar protein synthesis 4.5 hours after eccentric contractions compared to concentric contractions, although both contraction types elevated the synthesis above rest values.

However, plenty of research supports the idea that eccentric and concentric training elicit similar hypertrophic responses with no significant differences in muscle thickness (Kim et al. 2015; Timmins et al. 2016), muscle CSA (Jones & Rutheford, 1987; Moore et al. 2012; Farup et al. 2014b), muscle volume (Franchi et al. 2014), or fat-free soft tissue mass (Nicols-Richardson et al. 2007). Farup et al. (2014a) even showed increased hypertrophy after concentric strength training.

A meta-analysis by Schoenfeld et al. (2017) analyzed 15 studies comparing hypertrophic effects of eccentric and concentric strength training and concluded that effect size (ES) slightly favors eccentric contractions, but this result was not statistically significant (figure 5).

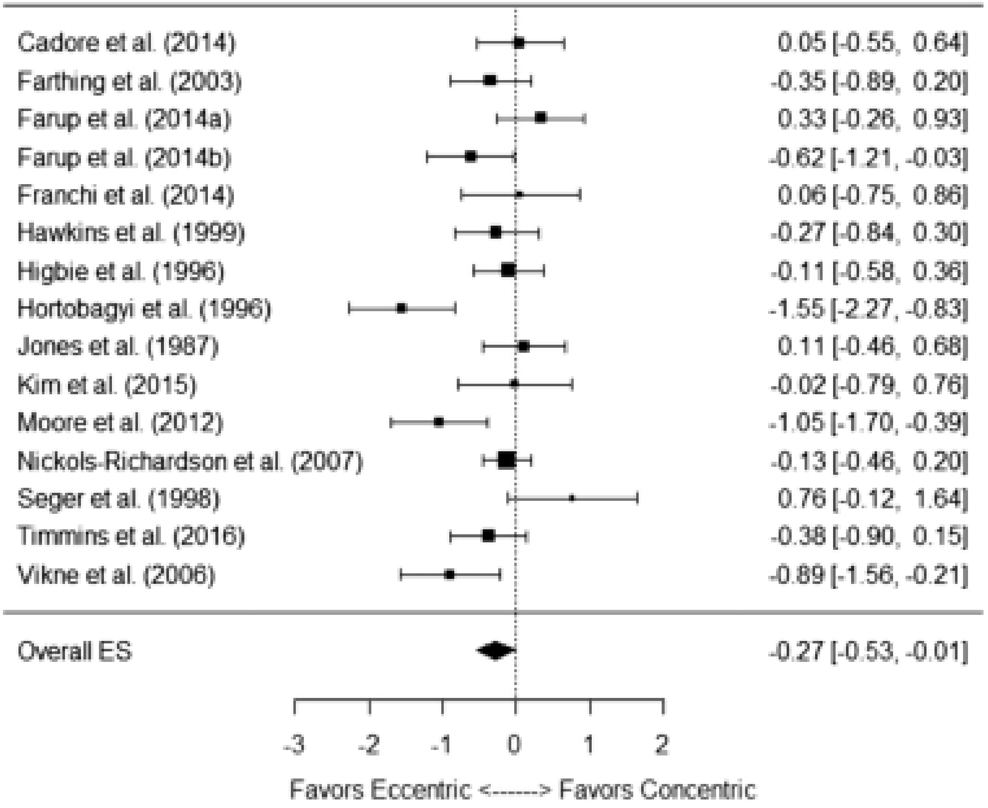


FIGURE 5. Studies comparing hypertrophic effects of concentric and eccentric strength training. Results favor eccentric strength training, but this did not reach statistical significance. (Schoenfeld et al. 2017).

However, there is some effect of speed of eccentric contractions on hypertrophy, as Stasinaki et al. (2019) reported significant changes in VL thickness after slow eccentric training (~4 second repetitions) but no changes in fast eccentric training group (<1 second repetitions). They did not compare different speeds of concentric exercise to allow for between training type analyses.

There might also be a type-location specific effect of hypertrophy, at least in quadriceps muscles. Eccentric training led to increased hypertrophy in the distal part (Seger et al. (1998), whereas concentric training has previously been reported to elicit changes in the proximal end of quadriceps muscle (Naciri et al. 1989).

3.2 Fiber type composition and muscle architecture

Pennation angle. Timmins et al. (2016) reported reduced PA in eccentric training group 14 days after a strength training intervention. Their concentric training group showed increased PA. Duhig et al. (2019) also showed eccentric training to decrease PA and concentric training to increase PA. On the other hand, Franchi et al. (2014) reported significantly increased PA in concentric group, but no changes in eccentric group. This is in line with the results from Potier et al. (2009), who showed no changes in PA after eccentric strength training.

Fascicle length. Eccentric strength training has been shown to increase FL (Potier et al. 2009; Franchi et al. 2014; Timmins et al. 2016; Alonso-Fernandez et al. 2018; Duhig et al. 2019). It has also been reported that FL relative to muscle thickness increased after eccentric strength training (Alonso-Fernandez et al. 2018). Franchi et al. (2014) showed that concentric training also resulted in lengthened fascicles, although eccentric training resulted in significantly greater changes (figure 6). In contrast, Duhig et al. (2019) showed significantly shortened fascicles after concentric training. Stasinaki et al. (2019) showed increased FL only after fast eccentric training, but no changes in FL after slow eccentric training.

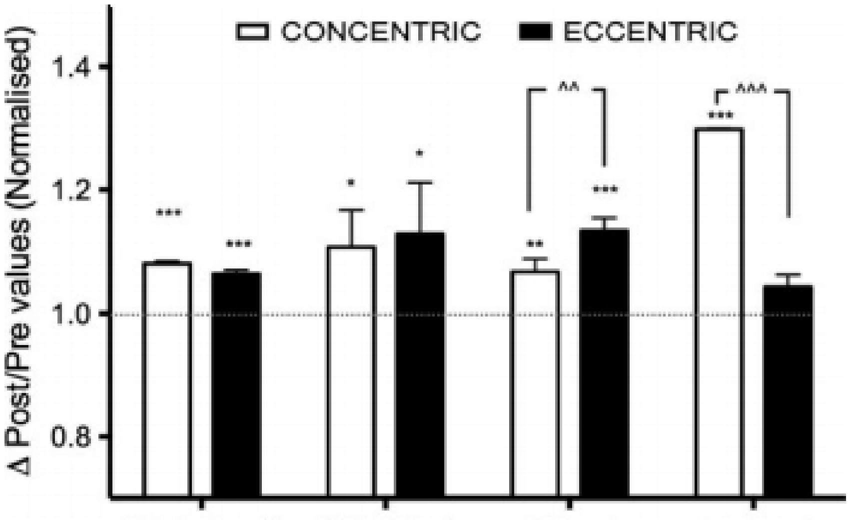


FIGURE 6. Changes in various measures of muscle architecture after concentric and eccentric strength training relative to baseline values. Statistical significance compared to baseline values *=p<0.05 **=p<0.001 ***=p<0.0001. Statistical significance between groups ^^= p<0.01 ^^^=p<0.001. (Franchi et al. 2014).

Fiber type distribution. After 4 weeks of strength training Raue et al. (2005) reported concentric training to decrease the amount of type IIx MHC variants. Eccentric training increased the number of total hybrids (figure 7). Since type IIx fibers are highly explosive, easily fatigued muscle fibers, shift towards type IIa/IIx MHC hybrids could reduce maximal power output and increase oxidativity of the muscle. (Raue et al. 2005). In contrast to these findings, Seger et al. (1998) reported slightly decreased IIa fiber percentage after eccentric training, with no significant changes in concentric training group. Adams et al. (1993) reported no changes between con-only and ecc-con training programs in fiber type distribution. For pooled group data they observed a shift from IIb MHC variants towards IIa MHC variants and the fiber type reflected these changes. Training did not change type I fiber portion.

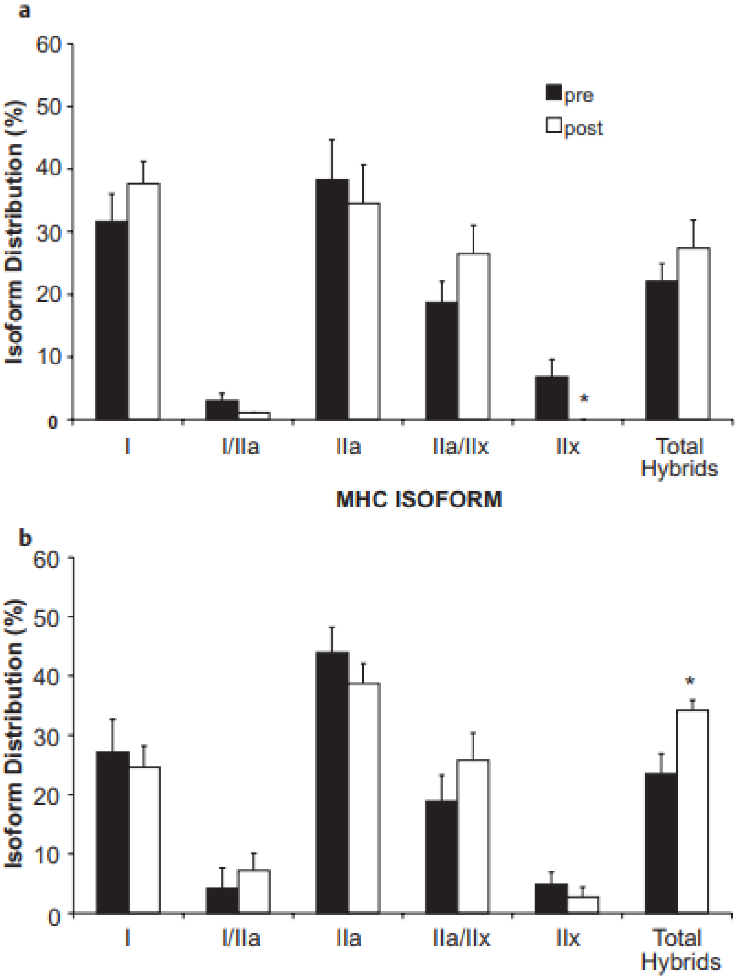


FIGURE 7. Changes elicited by a) concentric training and b) eccentric training in muscle MHC distribution. * = $p<0.05$. (Raue et al. 2005).

3.3 Neural control

Changes in strength after a training regimen are not solely dependable on the changes in muscle size (Jones & Rutheford, 1987) and architecture, but they are also related to neural factors, for example increase in voluntary neural drive of the agonist muscle (Barrué-Belou et al. 2016) or decreased neural drive of the antagonist muscle. Neural changes seem to contribute for the strength gains after the first 4 weeks of the training program, whereas structural changes contribute more after 12 weeks of training, at least in the quadriceps femoris muscle (Häkkinen & Komi, 1983; Petterson et al. 2011).

Maximal voluntary activation level has been reported to be lower in eccentric contractions than in concentric or isometric contractions (Eltman et al. 2004). This is due the usage of elastic components of the muscle. Nevertheless, eccentric training increases voluntary neural drive and this, at least partly, correlates to improvements in eccentric maximal voluntary torque (Barrué-Belou et al. 2016). Still, only difference in eccentric/concentric agonist muscle EMG activity ratio between eccentric and concentric training after 10 weeks of strength training was reported to be after concentric training with 270º/s torque. No differences were observed in antagonist EMG activation between concentric and eccentric training. (Seger & Thorstensson, 2005).

Correlation between EMG activity of the agonist muscle and produced force in given movement are not always clear. In bench press exercise only poor to moderate correlations have been reported between agonist muscle (*pectoralis major* and *anterior deltoid*) EMG activity and produced force (Pinto et al. 2013).

Neural control seems to be affected by movement speed, at least in eccentric exercise. Stasinaki et al. (2019) reported increased rate of force development during the first 200ms of isometric leg press after fast eccentric training. No changes were observed in slow eccentric training.

3.4 Strength

When assessing strength gains after training regimen, it has to be taken in to account what muscle contraction type is used to measure strength as training methods may have specific effects on certain contraction types. Studies show a variety of different results regarding strength measurements.

Concentric strength. Some authors have reported that eccentric strength training improves concentric strength more than concentric strength training (Farthing et al. 2003; Kaminski et al. 1996, isotonic; Roig et al. 2008). It has been shown that con-only strength gains were impaired by not including the eccentric phase in the strength training (Dudley et al. 1991). However, other studies (Duncan et al. 1989; Higbie et al. 1996; Housh et al. 1996; Hawkins et al. 1999; Raue et al. 2005) found concentric training to improve concentric strength more: eccentric training elicited only small or not significant changes in concentric strength. This has led to hypothesis of training specific strength gains. Other studies show no difference in concentric strength between eccentric and concentric strength training methods (Johnson et al. 1976; Ellenbecker et al. 1988; Kaminski et al. 1996, isokinetic; Seger et al. 1998; Farthing et al. 2003; Mjolsnes et al. 2004; Moore et al. 2012).

Isometric strength. Both Franchi et al. (2014) or Duhig et al. (2019) reported similar strength gains in isometric peak MVC force in concentric and eccentric training groups. Similar results were reported by Moore et al. (2012), who showed no significant differences between concentric and eccentric training in peak isometric torque. Other studies have reported contrasting results, as Mjolsnes et al. (2004) reported eccentric training to be superior training method in improving isometric strength and Seger et al. (1998) reported concentric training to increase isometric strength with no improvements after eccentric training.

Eccentric strength. Meta-analysis by Roig et al. (2008) showed eccentric training to very show specific strength gains in eccentric strength also regarding contraction velocity. However, results by Ellenbekcer et al. (1988), Hawkins et al. (1999), Farthing et al. (2003) and Moore et al. (2012) seem to negate the effects of training specifity. Ellenbecker et al. (1988) showed concentric training to improve eccentric strength, whereas eccentric training did not elicit improvements. Hawkins et al. (1999) reported eccentric training to improve eccentric strength, but concentric training to improve strength in both contraction types. Farthing et al. (2003), Moore et al. (2012) and Duhig et al. (2018) reported similar gains in eccentric strength after both training methods. Other studies have shown eccentric training to elicit higher strength gains in eccentric strength, with lower or no significant gains elicited by concentric training (Duncan et al. 1989; Higbie et al. 1996; Kaminski et al. 1996; Seger et al. 1998; Mjolsnes et al. 2004). According to review article by Baroni et al. (2015) eccentric strength training elicits higher gains in eccentric strength per training session than of concentric strength gains (0.45-3.42% vs. 0.23-1.44%), supporting the principle of training specific strength improvements.

Strength in eccentric-concentric movements. Ecc-con training has been shown to elicit increased eccentric and concentric peak torques, vertical jump height and 3RM over con-only training (Colliander & Tesch, 1990). However, Coratella & Schena (2016) reported similar gains in 1RM/BW ratio after 6 weeks of concentric only, eccentric only and traditional eccentric-concentric strength training.

3.5 Power

As discussed before, muscle power depends on muscle morphology and neural activation. Thus, the better option for increasing athlete's power output would be the strength training method maximizing these variables. While no significant results can be observed between increases in CSA after eccentric and concentric training and results from studies focusing on strength results depend on multiple variables like type of strength measured, it is difficult to establish scientific reasoning for superiority of either method in increasing power output. Although this field of study would be of great interest for athletes competing in power sports, only very limited literature is available. There is some evidence, that eccentric cycling training produces greater increases in counter-movement jump maximal power (Elmer et al. 2012) and squat-jump performance (Gross et al. 2010) compared with normal concentric cycling.

Strength training studies comparing effects of eccentric and concentric training on muscle power seem to be absolvent, but some directions can be interpreted from closely related research. Pritchard et al. (2015) studied effects of con-only and ecc-con training on con-only and ecc-con power. It seems that con-only training and ecc-con training both improved con-only and ecc-con power similarly on both 40% 1RM and 60% 1RM loads.

In addition, Sheppard et al. (2008) have reported increased power after training that uses loads during the eccentric phase of the counter movement jump. It has to be noted, that the other group performed counter movement jumps without any extra load and thus we cannot directly compare eccentric and concentric training. Also, Papadopoulos et al. (2014) showed increased strength and power after isokinetic eccentric training, but no concentric training group was implemented to allow for between group analyses.

4 DYNAMIC STRENGTH INDEX

Dynamic strength index (DSI) or dynamic strength deficit (DSD) is a tool to assess individual strength and power qualities and to profile athlete's training needs (Sheppard et al. 2011; Young et al. 2015; Thomas et al. 2015). DSI is expressed as the ratio of dynamic movement peak force to subsequent isometric peak force. Ultimately this means the result will be an arbitrary number with no unit. For lower body assessment counter-movement jump (CMJ-DSI) or squat jump (SJ-DSI) and isometric mid-thigh pull are most commonly used movements. For upper body, DSI has been calculated in the bench press exercise (BP-DSI) using data of ballistic bench press throws and isometric bench press (Young et al. 2014; Young et al. 2015).

4.1 Determinants of DSI

The DSI ratio ultimately depends on the athlete's ability to produce high isometric force and their ability to produce explosive power (Young et al. 2015). Isometric peak force is affected by muscle CSA (Jung et al. 2011) and joint angle (Fioranelli & Lee, 2008; Young et al. 2014). Thus, results of BP-DSI should be interpreted carefully and the elbow angle in isometric bench press should be accounted for (figure 8).

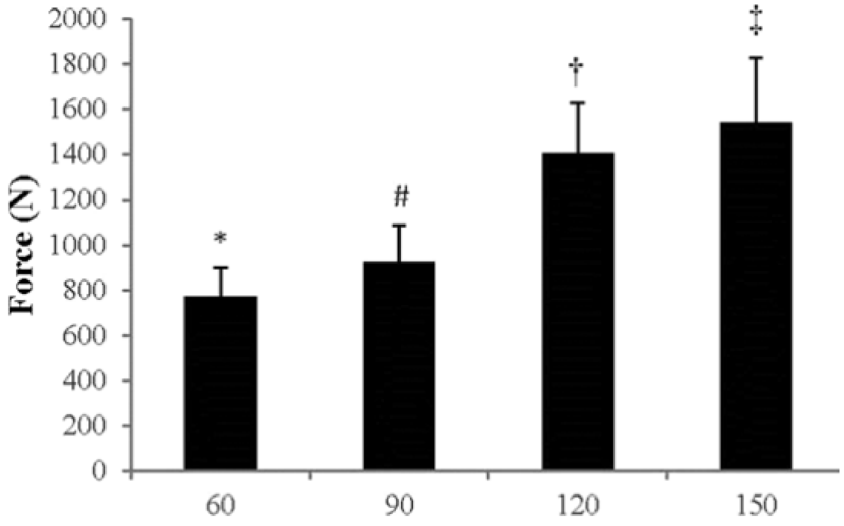


FIGURE 8. Mean force in isometric bench press across different elbow angles. (Young et al. 2014).

Maximum mean power in bench press throw is highly dependable on bench press 1RM result (Bartholomei et al. 2018) and peak power in BPT is correlated with *pectoralis major* muscle volume (Akagi et al 2014) (figure 9). In addition, the stiffness of muscle-tendon-system contributes to peak force and peak power of the concentric phase, as observed in lower-body assessment (Bojsen-Moller et al. 2005).

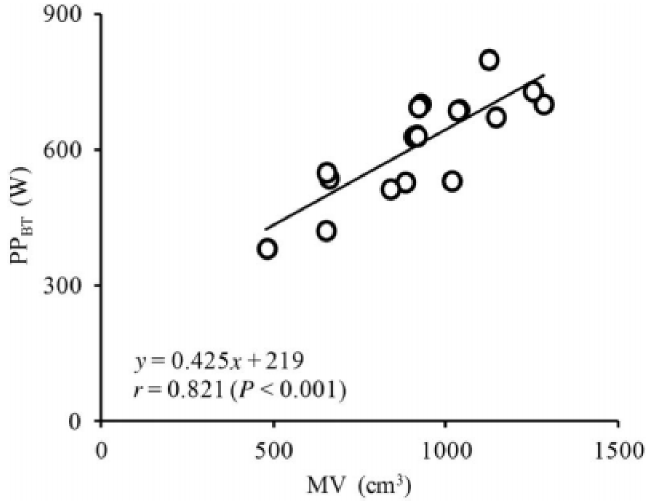


FIGURE 9. Bench press throw peak power correlates with *pectoralis major* muscle volume. (Akagi et al. 2014).

4.2 Reliability of DSI

Both methods for lower-body DSI assessment have been proven reliable with high intra-class correlation (ICC) values 0.952 (Sheppard et al. 2011) and 0.97 (Thomas et al. 2015) for SJ-DSI and 0.920-0.952 (Comfort et al. 2018a), and 0.940-0.986 (Comfort et al. 2018b) for CMJ-DSI.

Comfort et al. (2018a) concluded that CMJ-DSI should be used, since it was shown to be more reliable than using squat jump to calculate DSI, at least in the first measurement session. In the second session reliability of SJ-DSI improved to the same level as CMJ-DSI, most likely indicating a learning effect. CMJ-DSI showed good reliability in both sessions. Eventually there was no statistical difference between the two methods in DSI value. (Comfort et al. 2018a)

Young et al. (2014) reported BP-DSI to be a reliable method to assess strength qualities in athletes with a typical error (TE) of 0.28, acceptable variation (3.5 %CV) and high relative reliability (ICC of 0.86-0.96). Performance markers of ballistic bench press (peak displacement, peak force, peak power and peak velocity) were reported to be a reliable method at 45% 1RM loads, but results of peak rate of force development (PRFD) should be only used after extensive familiarization sessions or with athletes used to explosive upper-body exercise.

As discussed before, elbow angle in the isometric bench press affects the results of BP-DSI and authors should carefully describe used elbow angles. Young et al. (2014) reported high relative reliability of isometric bench press peak force and poor reliability of PRFD with all elbow angles compared in their study (60º, 90 º, 120 º and 150º).

4.3 Reference values of DSI presented in literature

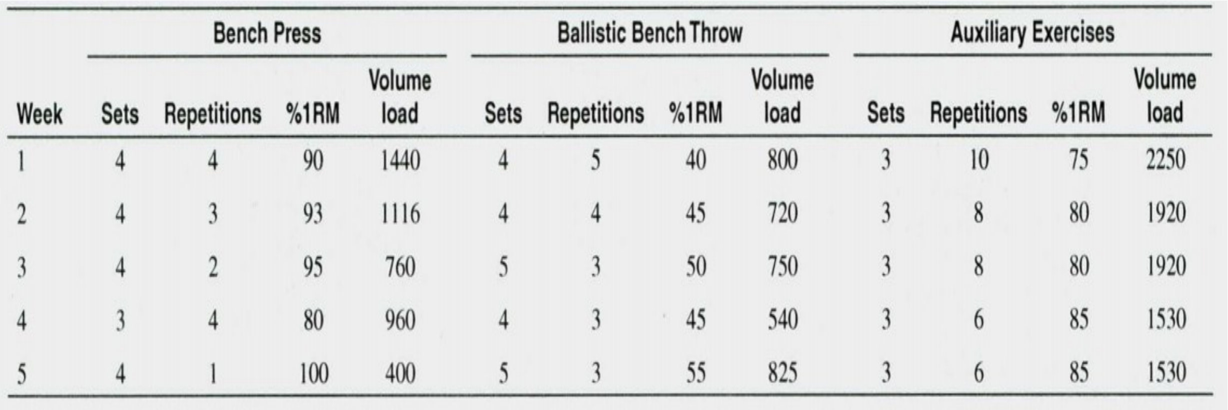
Lower-body DSI can differentiate athletes between sports with highest results found in female cricket players (0.91±0.13) and lowest values in male soccer players (0.70±0.16) (Thomas et al. 2015). Other studies have reported lower-body DSI values of 0.71±0.13 and 0.65±0.11 (Comfort et al. 2018b), 0.70±0.10 (Sheppard et al. 2011) and 0.78±0.19 (Thomas et al. 2015).

In bench press exercise, Young et al. (2015) reported DSI values of 0.65±0.14 and 0.64±0.15 pre-training for their two training groups (BPT training and BP training, respectively) consisting of 24 young male athletes from different sports. Post training their DSI had increased to 0.83±0.20 and 0.73±0.17, indicating a significant ($p \leq 0.001$) change in both groups. These results may represent values obtained using either 120º or 150º elbow angle in the isometric BP, as the authors only failed to sufficiently report which elbow angle was eventually used for data analysis.

4.4 Effects of strength training on DSI

DSI can detect training induced changes (Sheppard et al. 2011; Young et al. 2015; Thomas et al. 2015; Comfort et al. 2018b), but effects of different training protocols are not determined. Young et al. (2015) reported increased upper-body DSI after 5 weeks of both ballistic BPT training and high-load (≥90% BP 1RM) BP training (table 1). Between-group analysis showed ballistic BPT training to result in likely higher increases in BPT peak force and DSI values, while BP training induced likely higher responses in absolute 1RM BP values, although also increasing DSI values.

TABLE 1. Two training interventions used in the study by Young et al. 2015.



	Bench Press				Ballistic Bench Throw				Auxiliary Exercises			
Week	Sets	Repetitions	%1RM	Volume load	Sets	Repetitions	%1RM	Volume load	Sets	Repetitions	%1RM	Volume load
1	4	4	90	1440	4	5	40	800	3	10	75	2250
2	4	3	93	1116	4	4	45	720	3	8	80	1920
3	4	2	95	760	5	3	50	750	3	8	80	1920
4	3	4	80	960	4	3	45	540	3	6	85	1530
5	4	1	100	400	5	3	55	825	3	6	85	1530

On the other hand, decreases in lower-body DSI after strength training have been reported (Sheppard et al. 2011; Comfort et al. 2018b). Comfort et al. (2018b) reported a small but significant decrease in DSI of college athletes after a 4-week training program focusing on high-load (≥80% 1RM for weeks 1-3 and 75% 1RM for week 4) exercises for the lower-body. They also reported the individual DSI values, and it seems interpersonal variation in DSI values can be significant ranging from <0.50 to >0.90 (figure 10).

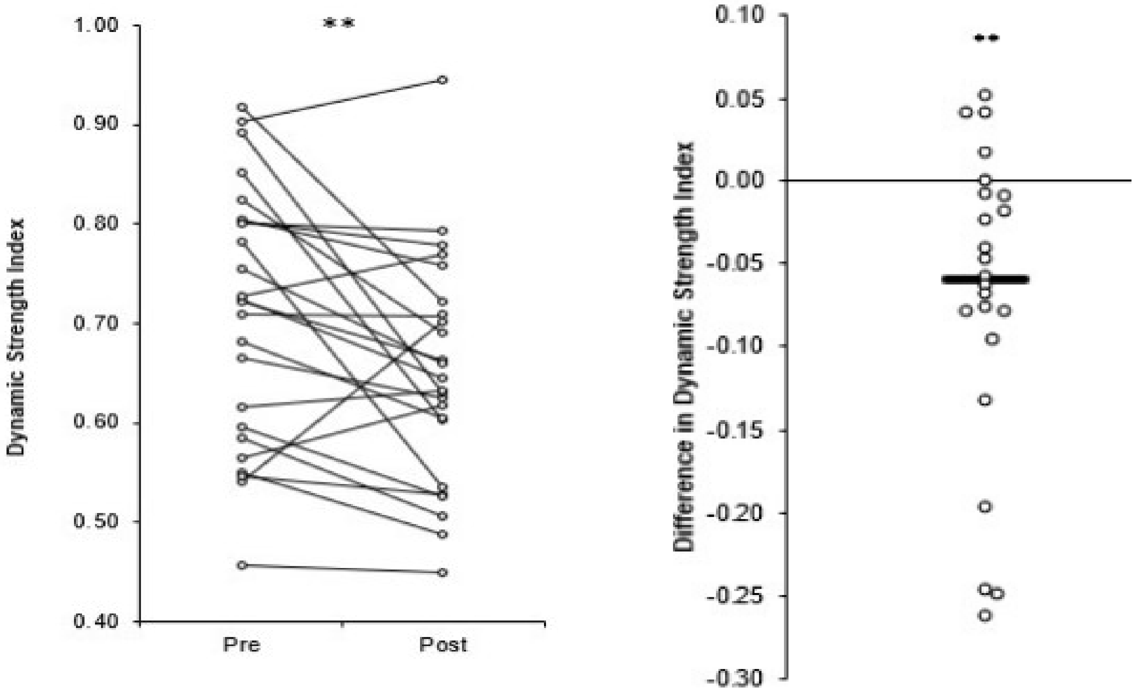


FIGURE 10. High variation in individual DSI values before and after the strength training intervention and in the magnitude of change. Modified from Comfort et al. 2018b.

Absolute results of isometric and dynamic force should be interpreted along DSI as increases in force may affect DSI negatively and improving both isometric and ballistic peak force similarly will not show changes in DSI. These should still be considered of a positive training effect. (Thomas et al. 2015).

4.5 Directing training interventions based on DSI

Young et al. (2015) suggested increasing athlete's maximal strength if the DSI ratio was higher than or equal to 0.75 and focusing on the ability to reach higher peak forces in high velocity movements if the DSI ratio was under 0.75. Other authors have reported similar practical applications for lower-body DSI, for example Sheppard et al. (2011) suggested emphasis on ballistic strength for athletes with low (<0.60) DSI value and emphasis on maximal strength for athletes with high DSI (>0.80) and low IMTP peak force. As reported by Thomas et al. (2015), DSI varies between sports, and the requirements of the sport should be kept in mind when interpreting DSI values in athletes.

Due to high variation in individual DSI values and to allow for assessing how training interventions should be directed on the basis of DSI, some studies have presented within-group analyses by reporting results from low-DSI and high-DSI groups after training interventions (Young et al. 2015; Comfort et al. 2018b).

Results by Young et al. (2015) showed high correlations between high BP-DSI before the training intervention and high percentile increase in isometric BP peak force after maximal strength training intervention. High-DSI maximal strength training group also increased their ballistic BPT peak force similarly to high-DSI ballistic BPT training group. Thus, the authors recommended maximal strength training interventions for high-DSI athletes with relatively low ballistic performance peak force.

Low-DSI athletes benefited from both ballistic BPT training and maximal strength training, with high improvements respective to their training group. Thus, the authors concluded low-DSI group should be further examined if values of isometric strength are adequate or not.

On the other hand, Comfort et al. (2018b) reported no significant changes in CMJ peak force, IMTP peak force or DSI for the low-DSI group after a 4-week maximal strength training protocol (figure 11). This likely indicates that they already had sufficient values of isometric strength and a 4-week strength training program was not enough to elicit meaningful changes. They would have possibly benefited from ballistic explosive training. (Young et al. 2015).

High-DSI group showed increased IMTP peak force, resulting in decreased CMJ-DSI (Comfort et al. 2018b).

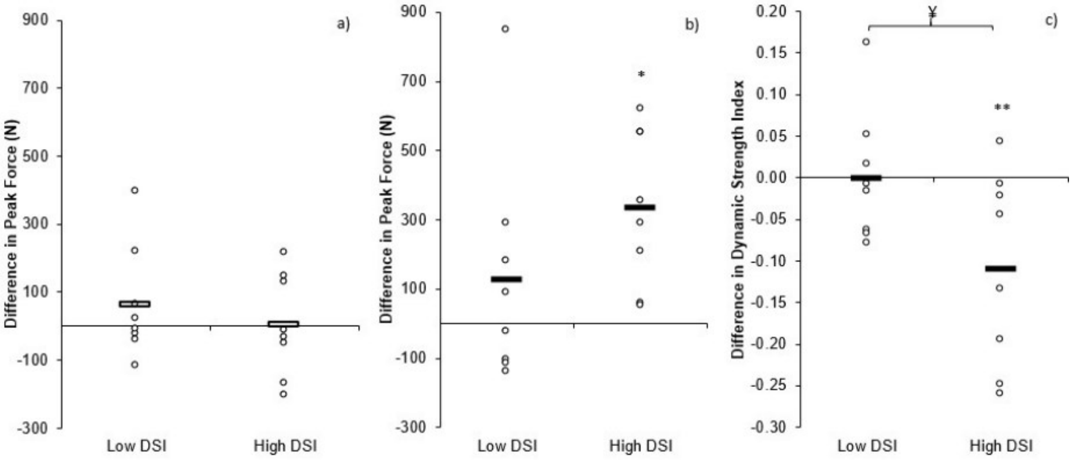


FIGURE 11. Changes in performance markers after a maximal strength training protocol for low- and high-DSI groups in a) CMJ, b) IMTP and c) DSI. (Comfort et al. 2018b).

5 RESEARCH QUESTIONS & HYPOTHESES

This research aims to map out previously unstudied areas of how concentric and eccentric strength training modalities may affect dynamic strength index (DSI) and how concentric and eccentric strength training modalities affect power output. Athletes and coaches especially in various sports may be interested how to achieve certain explosiveness-to-strength ratios and maximize the gains in power output via strength training.

Question 1. Do effects of isokinetic eccentric strength training on concentric bench press throw peak power, peak force and impulse differ from those elicited by isokinetic concentric strength training?

Hypothesis 1. Yes. Even though eccentric training does not likely increase concentric strength more than concentric training (isotonic; Johnson et al. 1976; Ellenbecker et al. 1988; Kaminski et al. 1996, isokinetic; Seger et al. 1998; Farthing et al. 2003; Mjolsnes et al. 2004; Moore et al. 2012), some evidence exists that eccentric cycling improves jump performance more than concentric cycling (Gross et al. 2010; Elmer et al. 2012). Additionally, eccentric training increases FL (Potier et al. 2009; Franchi et al. 2014; Timmins et al. 2016; Alonso-Fernandez et al. 2018; Duhig et al. 2019), which in turn results to increased contraction velocity (Lieber & Ward, 2011) and thus increased force production in short contraction times (Cormie et al. 2011a).

Question 2. Do effects of isokinetic eccentric training on dynamic strength index (DSI) differ from the effects of isokinetic concentric training?

Hypothesis 2. Yes. Strength gains in concentric strength are likely similar between training conditions (isotonic; Johnson et al. 1976; Ellenbecker et al. 1988; Kaminski et al. 1996, isokinetic; Seger et al. 1998; Farthing et al. 2003; Mjolsnes et al. 2004; Moore et al. 2012), leading to similar increases in isometric peak force. Since eccentric training increases concentric power more than concentric training through increased FL (Potier et al. 2009; Franchi et al. 2014; Timmins et al. 2016; Alonso-Fernandez et al. 2018; Duhig et al. 2019), DSI should increase for eccentric training group and show no change or only small changes for concentric group.

Question 3. Is DSI different for different loads of 1RM?

Hypothesis. Yes, as it has been shown by Newton et al. (1997) that peak force in concentric-only BPT was higher at 60%1RM than with 30 or 45% 1RM. Peak force increased when load was increased (Newton et al. 1997). Higher peak force means DSI will be higher since the dividend is increased, but divisor (isometric peaks force) remains unchanged.

6 METHODS

This study was conducted as part of a more comprehensive research organized in the Faculty of Health and Sport Sciences, University of Jyväskylä. Only the methods relevant for understanding the results of this particular study are presented. The study design gives an overview of the whole project.

6.1 Participants

Forty-eight non-competitive and healthy men and women, 18-35 years of age, were recruited for the study via university webpage and local newspaper advertisements. A total of 46 participants completed the training phase of the study, with their anthropometrical data presented in table 2. Drop out (2) was due to changes in work situation that made participating in the study impossible (1) and due to reasons not informed to researchers (1). Of the forty-six participants taking part to the training intervention, one participant did not participate to MID measurements due to sickness, but otherwise completed the study.

The participants were informed about study design and possible risks and benefits of the study. After that an informed consent was obtained from each subject. The study was conducted following the Declaration of Helsinki principles and was approved by the Ethics Committee of the University of Jyväskylä. All participants reported no medical conditions that prevented from participating in rigorous physical activity or upper-body musculoskeletal injuries.

Participants were assigned to eccentric and concentric groups with balanced 1RM results measured in the familiarization measurements. Additionally, female groups were balanced with users of hormonal contraception methods. Anthropometrical information of both men and women concentric and eccentric groups are presented in table 6. No statistical differences at CONT condition were observed in 1RM between concentric and eccentric groups (p=0.94) using the two-sample unequal variance t-test.

TABLE 2. Anthropometrical and performance data of the participants in the training phase of the study. Data presented as male and female participants combined and separate.

	CON			ECC		
Participants	n = 24	M=12	F=12	n = 22	M=11	F=11
Age (years)	30.0±4.1	31.6±3.1	28.1±4.3	27.7 ± 5.2	30.2±4.9	25.4±4.7
Height (m)	1.73±0.10	1.79±0.07	1.67±0.08	1.73±0.07	1.79±0.04	1.67±0.04
Weight (kg)	72.0±11.3	78.8±10.3	65.2±7.9	74.1±10.5	79.7±10.1	68.6±8.0
BMI (kg/m2)	23.8±2.7	24.3±3.1	23.3±2.4	24.7±3.2	24.9±3.1	24.7±3.5
CONT BP 1RM (kg)	55.2±20.4	70.2±16.9	40.3±9.9	55.7±20.1	70.8±15.9	40.5±9.5

6.2 Study design

On week -1 participants reported twice to the laboratory for familiarization sessions. On week 0 control (CONT) measurements were conducted but no other training was allowed. On week 1 participants performed PRE measurements and began the 10-week training program. On week 6 participants performed the MID measurements and on week 10 POST measurements. After that, participants were instructed not to perform any kind of strength training activities for 5 weeks. On week 15 participants reported back to the laboratory for POST2 measurements. Acute measurements, where bench press throw and isometric bench press performance and blood markers were followed before and after an isokinetic bench press exercise, were conducted on weeks 1 and 10. Study design is presented in figure 12.

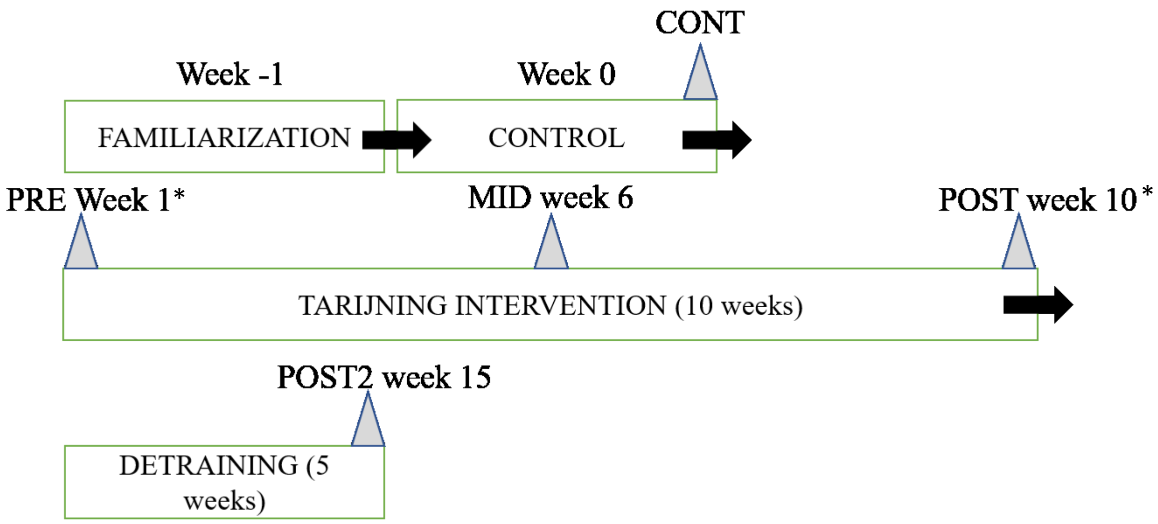


FIGURE 12. Design of the present study. Acute measurements are marked with *.

6.3 Training protocol

Warm-up. Each session participants performed a standardized warm up consisting of 5 minutes of cycling and upper-body resistance training movements targeting the shoulders and *pectoralis* muscles with light weights (2,5kg or 1,25kg per hand as participants selected themselves). Complete warm-up protocol is presented in table 3.

TABLE 3. Standardized warm-up protocol used in the study.

Movement	Time/Amount	Movement	Amount
Cycling	5 min	Dumbbell Front Raise	15
Arm circles:		Rotator Cuff:	
Forwards	15	Inwards	15
Backwards	15	Outwards	15
Arm swings back-front	15		
Shoulder press	15	Scapula push-ups	15
Dumbbell Lateral Deltoid Raise	15	Push ups	5-10

Isokinetic bench press exercise. Training was performed in a custom-made isokinetic bench press device (figure 13) using individual settings collected during the familiarization period. When selecting the appropriate settings, special care was taken that participants' elbows would not completely extend to prevent injuries due to overextension in the eccentric phase. Height of the start and end position of the barbell, width of the hands, adjustments of the bench height and elbow joint angle in barbell up position was collected. In training sessions participants performed either maximal eccentric or concentric contractions depending on their training group. Barbell velocity was set at 0.2 m/s with stops of 2000ms in both up and low positions of the barbell track. Exercise volume throughout the study is presented in table 4.

FIGURE 13. Custom-made isokinetic bench press device and the control panel.

Gym training. After the bench press exercise participants performed gym training under professional supervision. Gym training targeted back and lower-body muscles and the complete training program is presented in table 5. Weights were adjusted for each participant depending on their experience in strength training and familiarity with each exercise. Researchers instructed to add weights throughout the training intervention.

TABLE 4. Exercise volume as number of maximal contractions in isokinetic bench press. Weeks without indicated type of training means that participants only performed contractions relative to their respective training groups.

WEEK	SETS	REPS	PHASE	TYPE
0	2	3	CONT	2 x ecc + 2 x con sets
1	2	3	PRE	con for ECC group and ecc for CON group
1	3	4	acute	
2	3	3		
2	3	3		
3	3	3		
3	3	3		
4	4	4		
4	4	4		
5	4	4		
5	4	4		
6	2	3	MID	con for ECC group and ecc for CON group
6	3	4		
7	4	4		
7	4	4		
8	4	4		
8	4	4		
9	3	4		
9	3	4		
10	5	4	acute	
10	2	3	POST	con for ECC group and ecc for CON group
16	2	3	POST2	2 x ecc + 2 x con sets

TABLE 5. Gym training protocol used in the study.

	WEEKS 1-5		WEEKS 6-10	
	SETS	REPS	SETS	REPS
Lateral pull-down	3	8-10	3	6-8
Leg press	3	8-10	3	6-8
Hip thrust	3	8-10	3	6-8
Knee extension	3	8-10	3	6-8
Bicep curl	3	8-10	3	6-8
Trunk twist	3	8-12	3	6-12
Back extension	3	8-12	3	6-12

6.4 Measurement protocol

On weeks 0 (CONT), 1 (PRE), 6 (MID), 10 (POST) and 15 (POST2), participants were measured for isokinetic maximal force, bench press 1RM, bench press throw and isometric force in the given order.

Isokinetic maximal force. In CONT and POST2 setting participants performed both concentric and eccentric maximal contractions. Two sets of three repetitions of each contraction type were performed, first set being a familiarization and warm-up set. Data was collected from the second set of each contraction type. In PRE, MID and POST settings only contraction type contrary to trained contraction type was measured, as data from contraction type specific data was already collected from the training sessions. Isokinetic force was measured using the same isokinetic device training was performed with. EMG data from *biceps brachii*, *triceps brachii*, *pectoralis major* and *anterior deltoid* was measured using self-adhesive Ag/AgCl electrodes (Blue Sensor N-00-S, Medicotest). During CONT condition, grip width, bench height, high and low points of the barbell track and head positioning were collected to standardize positioning in each measurement. Participants were told to keep their legs on the bench throughout the measurement. Participants were loudly encouraged during the measurement.

Concentric 1RM bench press. Participants performed warm-up sets of 4 and 2 repetitions before actual 1RM trials. Load was estimated on the base of previous performance. Participants were told to lower the bar on their chest and lift it on the command of the researchers. Concentric only bench press was selected to ensure no bouncing would occur and because previous literature has shown eccentric phase to drastically enhance performance bench press performance (Cronin et al. 2000; Pestana-Melero et al 2020). 1RM testing was performed in a Smith machine (Kraftwerk, Vantaa, Finland, figure 14). During CONT session grip width and head position was collected to standardize positioning in each measurement. Participants were told to keep their feet on the bench. Participants were loudly encouraged during the measurement.

FIGURE 14. Customized Smith machine and force plate setting used to measure 1RM bench press and bench press throw performance.

Concentric bench press throw. Bench press throw was performed in Smith machine with 30%, 45% and 60% of concentric 1RM bench press when possible. Some female participants' 1RM were too low to allow for 30% assessment with the 12kg barbell and in such conditions only 45% and 60% throws were performed. Similar method of stopping the bar on participants' chest was used as in 1RM trials. MuscleLab M-encoder (Ergotest Innovations AS, Norway) was used to assess peak power of each throw.

Isometric bench press. Young et al. (2014) suggested using 120-degree elbow angle when measuring isometric bench press, but due to limited width of used bench press device, taller participants were not able to reach a 120-degree elbow angle. Thus, all participants performed isometric bench press with a 90-degree elbow angle, which was also reported reliable by Young et al. (2014). Custom-made isometric bench press device was used (University of Jyväskylä, Finland, figure 15). Participants were instructed to keep their feet on the bench. During control measurements width of the grip and head position was recorded from the preferred position of the participant to standardize positioning in each measurement. Participants were instructed to breathe in and push as hard and fast as they possibly could for three seconds on the command of the researchers. Participants were loudly encouraged during the measurement.

FIGURE 15. Custom-made isometric bench press device.

6.5 Data analysis

From each load of BPT one repetition with the highest peak power, indicated by M-encoder, was selected for further analyses with Signal 4.04 software (Cambridge Electronic Design Ltd, Cambridge, UK). The force before the onset of force production was determined to be 0. Impulse was determined as the area of force-curve between the onset of force and the point where arms were straightened. Peak force was determined as the peak amplitude between the onset of force and the point when arms where straightened. Signal 4.04 was also used to assess peak force as highest force of each isometric bench press trial. Highest peak force was selected for DSI calculations.

6.6 Statistical analysis

Microsoft Office Excel 2019 (Microsoft Corp. 2019. Redmond, WA) was used to calculate averages, average changes, standard deviations and to create charts. SPSS software 26.0 (IBM Corp. 2019. Armonk, NY) was used to calculate Shapiro-Wilkins-test to confirm normality of the data. Mixed methods ANOVA was used to analyze the within-group differences of peak power, peak force and impulse in BPT, peak force in isometric BP and DSI for three time points (PRE, MID & POST) to determine effects of isokinetic eccentric and concentric training on BPT performance, maximal isometric strength and DSI. Huynh-Feldt correction was used if necessary. For data that was not normally distributed, Mann-Whitney U-test was conducted to determine the statistical significance between groups. Wilcoxon signed rank test was conducted to calculate statistical significances within group between PRE and POST conditions.

Shapiro-Wilk-test showed that peak force with 45% and 60% 1RM loads, DSI with 45% and 60& 1RM loads and impulse with all loads were not normally distributed. Thus, Mann-Whitney U test was conducted for computed Δpre-post variables for between groups interaction and Wilcoxon signed rank test was conducted to assess within-group change between PRE and POST conditions. Other variables were eligible for mixed measures ANOVA.

7 RESULTS

7.1 1RM bench press

There was a significant interaction of time for 1RM performance (H-F: F=88,125, df=1,497, p<0.001). For both CON and ECC groups, 1RM at MID condition was higher than PRE (p<0.001) and 1RM at POST condition was higher than PRE or MID (p<0.001) (table 6). No statistically significant differences were observed between the two training modes (H-F: F=0.795, df=1.497, p=0.423, ECC +12.6%, CON +11.1%).

7.2 Impulse in BPT

There were no significant differences between the two training modalities in impulse with 30% 1RM (p=0.310, U=162), impulse with 45% 1RM (p=0.554, U=226) or impulse with 60% 1RM (p= 0.445, U=209).

No significant changes from PRE to POST for either training group with impulse with 30% 1RM (ECC: Z=-1.650, p=0.99, +7.9% CON: Z=-0.626, p=0.532, +3.4%), impulse with 45% 1RM (ECC: Z=-1.651, p=0.099, +11.4%, CON Z= -0.971, p=0.331, +5.8%) and impulse with 60% 1RM (ECC: Z=-1.234, p=0.217, +10.2%, CON: Z=-0.456, p=0.648, +8.5%) were detected.

TABLE 6. Main findings of the present study summarized. * = compared with pre p<0.05, ** = compared with pre condition p<0.01, *** = compared with pre condition p<0.001, ^ = compared with MID p<0.05, ^^ = compared with MID p<0.01, ^^^ = compared with MID p<0.00, # = trend compared with PRE p<0.075. ECC = eccentric training group, CON = concentric training group, 1RM = dynamic bench press one repetition maximum, pF = peak force with respective load of %1RM, isom pF = isometric peak force, pP = peak power, imp = impulse with respective load of %1RM, DSI = dynamic strength index

	PRE		MID		POST	
	ECC	CON	ECC	CON	ECC	CON
1RM (kg)	56.7±19.4	57.6±20.2	61.1±20.2***	59.3±19.8***	63.9±19.9***^^^	64.0±21.3***^^^
pF30% (N)	245.7±112.7	228.7±64.2	228.9±79.2	243.0±85.2	242.2±95.1	244.7±78.4
pF45% (N)	174.9±69.0	194.5±74.8	178.3±57.2	186.9±84.7	190.6±87.1	190.0±61.2
pF60% (N)	153.7±62.8	149.5±59.3	144.0±72.9	165.9±87.8	149.5±60.7	171.0±71.8*
isom pF (N)	613.3±190.4	599.0±198.2	619.1±197.4	597.4 ±190.4	659.1±190.8*^^	636.8±209.9*^
pP 30% (W)	527-9±178.4	490.1±202.1	529.9±188.3*	524.7±180.7*	548.4±207.9**	540.2±178.4**
pP 45% (W)	479.8±190.7	447.5±203.7	509.0±194.1*	467.3±174.2	552.5±211.6***^^	493.7±179.3*^
pP 60% (W)	448.0±164.7	412.3±138.5	476.8±168.1#	428.1±147.4**	497-8±178.6**	448.7±148.3***
imp30% (Ns)	49.2±18.4	50.1±14.9	48.7±14.0	52.9±26.1	53.1±17.1	51.8±15.3
imp45% (Ns)	46.6±15.3	52.2±15.3	50.0±14.8	47.7±14.8	51.9±14.8	55.2±22.3
imp60% (Ns)	53.3±19.9	52.0±30.8	47.0±18.2	63.1±54.9	58.7±18.8	56.4±21.5
DSI30%	0.38±0.13	0.37±0.06	0.36±0.08	0.38±0.08	0.36±0.06	0.37±0.08
DSI45%	0.29±0.06	0.33±0.08	0.29±0.05	0.31±0.09	0.29±0.07	0.31±0.09
DSI60%	0.25±0.07	0.25±0.07	0.23±0.07	0.27±0.09	0.23±0.05	0.28±0.10

7.3 Peak force in BPT

No significant changes in pF30% throughout the present study were observed (H-F: F=0.508, df=1.759, p=0.581). No statistically significant differences were observed between the two training modes for loads of 30% 1RM (F=0.912, df=1.759, p=0.396, ECC -1.4%, CON +7.0%)

Likewise, no significant differences between training groups for pF45% or pF60% were observed (p=0.265, U=203 and p=0.098, U=171 respectively). There was a significant change in pF60% for CON group, but not for ECC group (pF45% ECC: Z=-1.373, p=0.170, +9.0%, pF60% ECC: Z=-0.365, p=0.715, +2.7%, pF45% CON: Z=-0.486, p=0.627, -2.4%, pF60% CON: Z=-2.403, p=0.016, +14.4%)

7.4 Peak power in BPT

There were significant changes in peak power with 30% 1RM (F=8.118, df=2.0, p<0.001), peak power with 45% 1RM (H-F: F=10.217, df=1.517, p<0.001) and peak power with 60% 1RM (F=9.790, df=2.0, p<0.001) throughout the training intervention. For CON group, both MID (p<0.05) and POST (p<0.01) were higher than PRE at 30% 1RM, POST was higher than MID and PRE at 45% 1RM and both MID (p<0.01) and POST (p<0.001) were higher than PRE condition at 60% 1RM (figure 16). For ECC group, both MID (p<0.05) and POST (p<0.01) were higher than PRE condition at 30% 1RM, both MID (p<0.05) and POST (p<0.001) were higher than PRE and POST was higher than MID (p<0.01) at 45% 1RM and POST was higher than PRE (p<0.01) at 60%. There was also a statistical trend for MID to be higher than PRE at 60% 1RM in ECC group (p=0.055).

No significant differences between training methods were observed (pP30%: F=0.122, df=2.0, p=0.885, ECC +3.9%, CON +10.2%, pP45%, H-F: F=0.246, df=1.517, p=0.721, ECC+15.2%, CON +10.3%, pP60%: F=0.224, df=2.0, p=0.800, ECC +11.1%, CON +8.8%).

For concentric group, highest peak power at all timepoints was measured with 30% 1RM load. At PRE, peak power with 30% 1RM was significantly higher than with 60% 1RM (p<0.01).

At MID, peak power with 30% 1RM and 45% 1RM were higher than with 60% 1RM ($p<0.01$ and $p<0.001$, respectively). At POST, peak power with 30% 1RM was higher than with 45% 1RM or 60% 1RM ($p<0.01$ and $p<0.001$, respectively). Also, peak power with 45% 1RM was significantly higher than with 60% 1RM ($p<0.01$). For eccentric group, highest peak power was obtained with 30% 1RM at PRE and MID conditions, but with 45% 1RM at POST condition. At all conditions, peak power with both 30% and 45% 1RM were higher than with 60% 1RM (PRE $p<0.001$; MID $p<0.01$; POST 30% 1RM $p<0.01$ and 45% $p<0.001$) with no statistical differences between peak power with 30% and 45% 1RM at any time point.

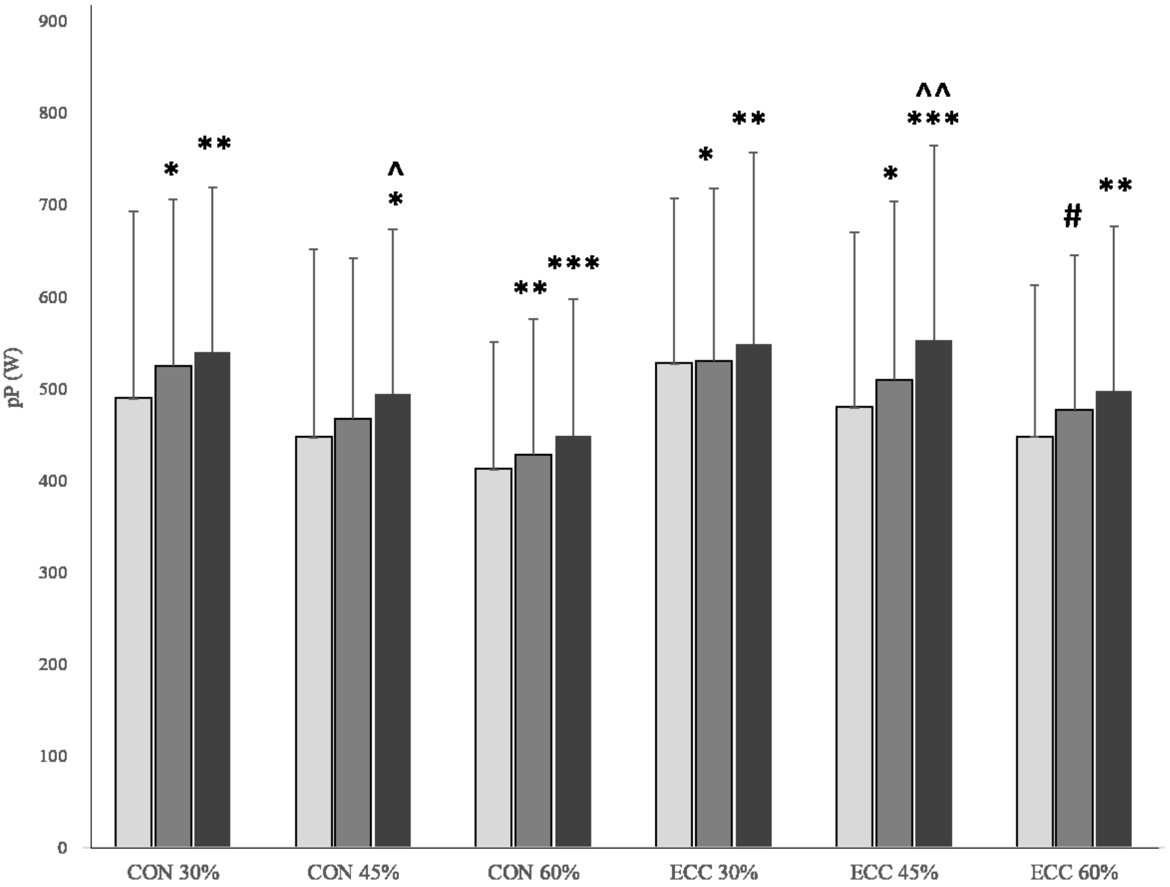


FIGURE 16. Within-group comparison of peak power values in BPT. Light gray = PRE, gray = MID, dark gray = POST, compared to PRE condition ***$p<0.001$, **$p<0.01$, *$p<0.05$, # = statistical trend ($p<0.075$) and compared to MID condition ^^$p<0.01$. ECC = eccentric training group, CON = concentric training group, pP = peak power in BPT.

7.5 Isometric peak force

There was a statistically significant increase in isometric peak force independent of training mode (H-F: F=8.525, df=1.456, p=0.002). For CON group POST was significantly higher than PRE (p<0.05; +6,3%) or MID (p<0.05). For ECC group POST was significantly higher than PRE (p<0.05; +7,5%) and MID (p<0.01). No statistically significant changes were observed between groups (H-F: F=0.4557, df=1.456, p=0.574).

7.6 Dynamic Strength Index

No significant changes were observed in DSI30% (H-F: p=0.779, F=0.203, df=1.681) or differences between the two training modes (H-F: p=0.774, F=0.209, df=1.681). Also, no significant differences between eccentric and concentric training in DSI45% (p=0.342, U=191) and DSI 60% (p=0.092, U=153) were observed. There were no significant PRE-to-POST changes in either training group for 45% or 60% 1RM loads (DSI45%: ECC Z=-0.037, p=0.970, CON Z=-1.338, p=0.181; DSI60%: ECC Z=-1.045, p=0.296, CON Z=-1.445, p=0.149).

For both training groups, at each time point, DSI measured with 30% 1RM was significantly higher than with 45% 1RM and 60% 1RM. Also, for ECC group, at each time point DSI measured with 45% 1RM was significantly higher than 60% 1RM. CON group revealed higher DSI with 45% 1RM than with 60% at PRE condition, but not at MID or POST condition. Although, there was a statistical trend for DSI to be higher with 45% 1RM than 60% at MID condition (figure 17).

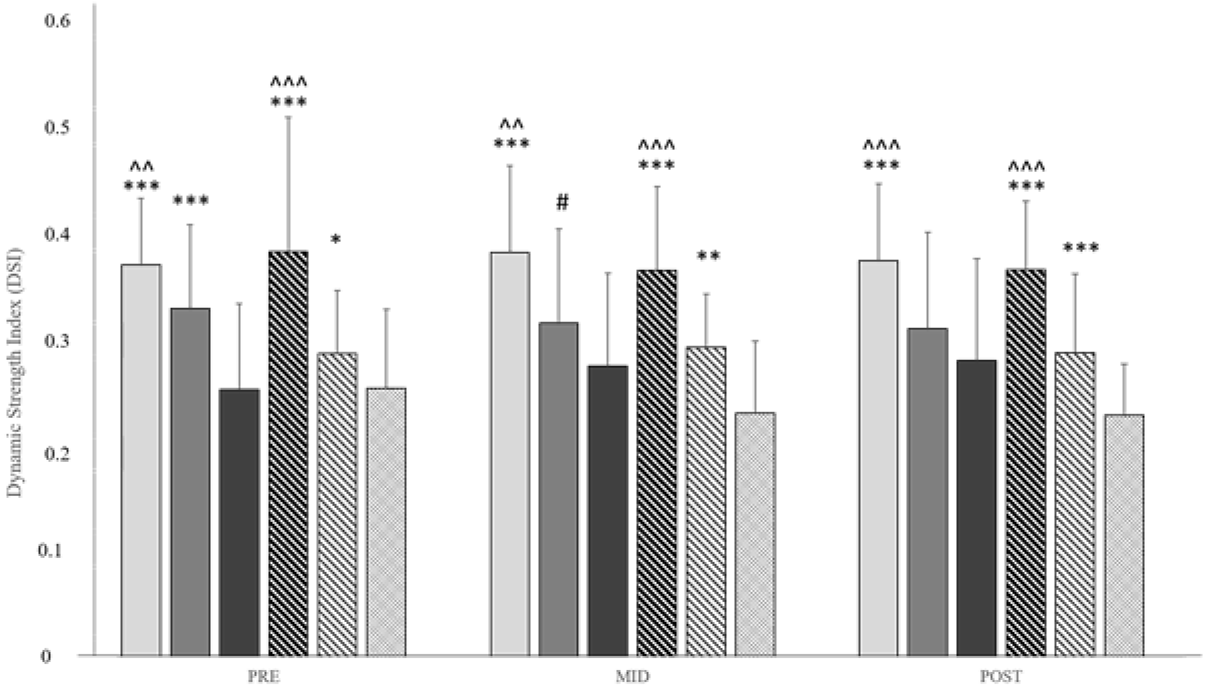


FIGURE 17. Dynamic Strength Index measured with different loads of 1RM at the same time point. Light gray = CON 30%, gray = CON 45%, dark gray = CON 60%, dark with lines = ECC 30%, gray lines = ECC 45% and gray with lines = ECC 60%. Significantly higher compared to 60% 1RM ***p<0.001, **p<0.01 and compared to 45% 1RM ^^^p<0.001, ^^p<0.01, #p<0.075. ECC = eccentric training group, CON = concentric training group.

8 DISCUSSION

The main finding of the present study was that, unlike hypothesized, no differences between the eccentric and concentric training methods were found in BPT peak power, impulse or peak force, DSI, isokinetic bench press, or BP 1RM after 10 weeks of (isokinetic) strength training. Additionally, it was found DSI to be radically affected by used load %1RM as hypothesized.

8.1 One repetition maximum (1RM)

Participants' maximal concentric strength represented as 1RM bench press increased during the 10 weeks of the study independent of the training method. Training stimulus and periodization of training volume were sufficient to increase maximal strength in both groups. The training modes increased strength at a similar pace, as both groups showed increased 1RM from PRE to MID and from MID to POST conditions.

The results in the present study were in line with a body of research showing no differences in concentric strength after eccentric and concentric training interventions (Johnson et al. 1976; Ellenbecker et al. 1988; Kaminski et al. 1996, isokinetic; Seger et al. 1998; Farthing et al. 2003; Mjolsnes et al. 2004; Moore et al. 2012). There was no evidence of impaired development of strength through 10 weeks of strength training without the eccentric phase in the CON group, as suggested by Dudley et al. (1991).

Mechanics in concentric only BP are notably different from eccentric-concentric BP exercise. The propulsion phase, concentric phase, and time to peak force, velocity, and power were shorter in eccentric-concentric BP (Pérez-Castilla et al. 2020).

8.2 Peak Force in BPT

According to the basic principles of the force-velocity curve, an increase in participants' peak force in BPT at POST condition compared to PRE condition when 1RM increased should be observed. That was not the case in the present study, as peak force in BPT remained unchanged.

The only significant change measured in BPT peak force was in the CON group with 60% 1RM load at POST condition compared to PRE condition. No differences between training modes or within training modes with loads of 30% or 45% 1RM were observed.

The reason for this could have something to do with load-specific training adaptations. Maximal isokinetic efforts were used, which means that participants were constantly pushing against the bar with as much force they could produce. Essentially each training session was focused on the high load – low-velocity ranges of the force-velocity curve.

On average, changes of -4.6 ± 39.3 N (-2.4%) and +14.5 ± 42.6 N (+9.0%) from PRE to POST condition were reported for CON and ECC groups respectively. Young et al. (2015) reported much higher values of peak force with 45% 1RM BPT for their two training groups: 1067.7 ± 244.7 N and 980.3 ± 178.5 N at PRE and 1369.1 ± 292.5 N and 1181.4 ± 280.6 N at POST, with significant changes from PRE to POST in both groups ($p \leq 0.001$) (Young et al. 2015). It should be noted that there was a methodological difference in performing the BPT. Young et al. (2015) used ballistic bench press throw, whereas we conducted a concentric only BPT with a stop at the bottom position of the bench press movement. It was shown by Pestana-Melero et al. (2020) that peak force in the bench press throw is lower in concentric-only BPT compared to eccentric-concentric BPT. In addition to performing BPT differently, there is likely a methodological difference in force plate data analysis. If the weight of the participants' average (79.1 kg) in the study by Young et al. (2015) is removed from the force values, we get 1067.7N - (79.1kg x 9.81m/s^2) = 291.73 N, which provides already a much smaller difference in values between the two studies.

8.3 Isometric Peak Force

Isometric peak force was 599.0 N and 613.3 N at PRE condition for CON and ECC training groups. The corresponding results at POST condition were 636.8 N and 659.1 N. These results are remarkably lower than reported by Young et al. (2015), showing average values of 1650.8 ± 298 N and 1555.2 ± 282.3 N at PRE condition and 1676.5 ± 301.8 N and 1619.4 ± 261.7 N at POST condition. This relatively large difference between the results could be due to a) training background and sex of the participants and b) using different elbow angles in isometric bench. As discussed above, Young et al. (2015) recruited young male athletes as participants, whereas untrained men and women were recruited for the present study. Similarly, they used either a 120 or 150-degree elbow angle, which has been shown to result in significantly higher isometric peak force values than with 90-degree elbow angle (Young et al. 2014) that was used in the present study.

Young et al. (2015) reported changes of 25.7 ± 31.4 N and 64.2 ± 127.6 N in isometric bench press peak force for their two training groups after 5 weeks of training. These findings correspond to the percentual changes of about 1.5% and 4.1%. Changes of 34.1 ± 59.1 N (6.3%) and 40.5 ± 87.7 N (7.5%) were observed for CON and ECC groups after 10 weeks of training, respectively. Larger increases of isometric peak force in the present study are likely due to participants' different training backgrounds and the prescribed 5-weeks longer training intervention in the present study.

8.4 Peak power in BPT

Many sports require extensive levels of peak power output for high-level performance. Ten weeks of maximal isokinetic strength training seems to increase peak power in recreationally trained men and women. That is likely due to small changes in multiple factors such as agonist-antagonist co-activation, increases in muscle size, and neural drive. The volume of *pectoralis major* (Akagi et al. 2014) and muscle CSA (Moss et al. 1997) have been found to correlate with the maximal power output. Both eccentric and concentric strength training methods decreased agonist activation (Seger & Thorstensson, 2005), although the effect of agonist-antagonist co-activation in the bench press exercise total force is reported to be small to moderate (Pinto et al. 2013).

8.5 Impulse in BPT

Impulse did not significantly change throughout the intervention in either of the training groups. It remains unclear why impulse remained unchanged when peak power, 1RM bench press result, and isometric bench press increased from PRE to POST condition. It would be reasonable to assume increases in BPT average force, even when peak force in BPT did not change. Since impulse is defined as integral of force over time, participants' concentric push-off time was likely longer at POST condition to negate the effects of increased average force.

No previous studies have examined the changes in impulse after strength training interventions, and further research should more accurately determine if changes in impulse occur after strength training. There should also be a closer inspection on why impulse does not seem to change after maximal isokinetic strength training.

8.6 Dynamic strength index

Young et al. (2015) reported values of 0.65 ± 0.14 and 0.64 ± 0.15 at PRE condition and 0.83 ± 0.20 and 0.73 ± 0.17 at POST condition. Respective changes during the 5-week training protocol were, on average, +0.18 and +0.09. These results led to significant changes in DSI from PRE to POST ($p \leq 0.001$). Much lower DSI values were reported in the present study. At PRE, average values were 0.33 ± 0.08 and 0.29 ± 0.06 for CON and ECC groups, respectively. At POST, the corresponding values were 0.31 ± 0.09 and 0.29 ± 0.05, implying insignificant changes of -0.02 (-5.8%) and +0.00 (+0.3%).

As discussed before, the methodological differences between the studies (ballistic BPT vs. concentric only BPT, inclusion/exclusion criteria of participants' body weight in power plate data alanyses, and participants' training background) inevitably lead to differences in DSI. At PRE condition, larger elbow angle and training background in isometric bench press corresponded to 2.54 – 2.76 times higher isometric peak force if CON and ECC groups were compared to training groups from Young et al. (2015). Respectively, peak force in BPT was 5.04 – 6.10 times higher at PRE condition when comparing CON and ECC groups to training groups from Young et al. (2015). When taking in to account the average weight of the participants' (79.1 kg) and subtracting 79.1 kg x 9.81 m/s^2 from originally reported data, the calculated DSI's, on average, would be at PRE condition (1067.7 N – (79.1 kg x 9.81 m/s^2))/1650.8 N = 0,18 and (980.3 N – (79.1 kg x 9.81 m/s^2))/1555.2 N = 0.13. These values are more comparable to ones presented in the present study, when keeping in mind higher isometric peak forces generated with 120 or 150-degree elbow angles that lead to lower DSI values.

8.7 Strengths and limitations of the present study

Participants consisted of a variety of strength training backgrounds, ages and included both women and men. That is inevitably an issue with the present study as the deviation within results is rather large. On the other hand, for this reason, the number of recruited participants was higher than in previous articles in the current field of study. Additionally, female participants using hormonal contraception were equally divided between the training groups, which most strength training studies with women participants haven’t taken into account.

The training intervention was performed with an isolated isokinetic machine. This method does not offer practical solutions for athletes and coaches but is suitable for research purposes as validation and standardization of the movement are easier. Standardized movement with a stop at the lowest position in 1RM bench press and BPT also increases the reliability of the study. However, the present results are harder to compare with other studies since they have primarily performed ballistic BPT or 1RM repetitions without a stop in the low position.

8.8 Conclusion

The main finding of the present study was that changes in strength and power variables, including DSI, were similar between concentric and eccentric isokinetic strength training modalities after 10 weeks of (isokinetic) strength training. 1RM bench press, peak power in BPT, and peak force in isometric bench press increased regardless of the training mode used. Strength training did not affect BPT impulse or DSI. Only the CON group showed an increase in POST condition BPT peak force compared to the PRE condition, but no significant differences between training modes were observed.

When researching and using DSI in practical applications, it is vital to understand the relative load and elbow angle in the isometric bench press, since they both affect subsequently calculated DSI radically. Previous literature has mostly used loads of 45% 1RM.

8.9 Practical applications

This study provides average rates of changes in strength and power variables that researchers, coaches, athletes, and recreationally strength training men and women should be expecting to see when participating in strength training for up to 10 weeks. Maximal effort (isokinetic) bench press training is associated with positive changes in strength and power variables without changes in DSI.

REFERENCES

Abbott, B. C., Bigland, B. & Ritchie, J. M. 1952. The Physiological Cost of Negative Work. J Physiol. 117: 380-390.

Adams, G. R., Hather, B. M., Kenneth, M., Baldwin, K. M. & Dudley, G. A. 1993. Skeletal muscle myosin heavy chain composition and resistance training. J. Appl. Physiol. 74(2): 911-915.

Akagi, R., Tohdoh, Y., Hirayama, K & Kobayashi, Y. 2014. Relationship of pectoralis major muscle size with bench press and bench press throw performances. J Strength Cond Res. 28(6): 1778-1782.

Alonso-Fernandez, D., Docampo-Blanco, P & Martinez-Fernandez, J. 2018. Changes in muscle architecture of biceps femoris induced by eccentric strength training with nordic hamstring exercise. Scand J Med Sci Sports. 28: 88-94.

Baroni, B. M., Pinto, R. S., Herzog, W. &Vaz, M. A. 2015. Eccentric resistance training of the knee extensor muscle: Training programs and neuromuscular adaptations. Isokinetics and Exercise Science. 23: 183-198.

Barrué-Belou, S., Amaratini, D., Marque, P. & Duclay, J. 2016. Neural adaptations to submaximal isokinetic eccentric strength training. Eur J Appl Physiol. 116: 1024-1030.

Bartholomei, S., Nigro, F., Ruggeri, S., Malagoli Lanzoni, I., Ciacci, S., Merni, F., Sadres, E. Hoffman, J. R. & Semprini, G. 2018. Comparison between bench press throw and ballistic push-up tests to assess upper-body power in trained individuals. J Strength Cond Res. 32(6): 1503-1510.

Bevan, H. R., Bunce, P. J., Owen, N. J., Bennett, M. A., Cook, C. J., Cunningham, D. J., Newton, R. U. & Kilduff, L. P. 2010. Optimal loading for the development of peak power output in professional rugby players. J Strength Cond Res. 24(1): 43-47.

Blazevich, A. J. 2006. Effects of physical training and detraining, immobilization, growth and aging on human fascicle geometry. Sports Medicine. 36(12): 1003-1007.

Bojsen-Moller, J., Magnusson, S. P., Rasmussen, L. R., Kjaer, M. & Aagaard P. 2005. Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures. J Appl Physiol. 99: 986-994.

Castillo, F., Valverde, T., Morales, A., Pérez-Guerra, A., de León, F. & García-Manso, J. M. 2011. Maximum power, optimal load and optimal power spectrum for power training in upper-body (bench press): a review. Rev Andal Med Deporte. 5(1): 18-27.

Colliander, E. B. & Tesch, P. A. 1990. Effects of detraining following short term resistance training on eccentric and concentric muscle strength. Acta Physiol Scand. Sep. 140(1):31-9.

Comfort, P., Thomas, C., Dos'Santos, T., Jones, P. A., Suchomel, T. J. & McMahon, J. J. 2018a. Comparison of Methods of Calculating Dynamic Strength Index. International Journal of Sports Physiology and Performance. 13: 320-325.

Comfort, P., Thomas, C., Dos'Santos, T., Suchomel, T. J., Jones, P. A. & McMahon, J. J. 2018b. Changes in dynamic strength index in response to strength training. Sports. 6: 176.

Coratella, G. & Schena, F. 2016. Eccentric resistance training increases and retains maximal strength, muscle endurance, and hypertrophy in trained men. Appl Physiol Nutr Metab. 41: 1184-1189.

Cormie, P., McGuigan, M. R. & Newton, R. U. 2011a. Developing Maximal Neuromuscular Power. Part 1 – Biological Basis of Maximal Power Production. Sports Med. 41(1): 17-38.

Cormie, P., McGuigan, M. R. & Newton, R. U. 2011b. Developing Maximal Neuromuscular Power. Part 2 - Training Considerations for Improving Maximal Power Production. Sports Med. 41(2): 125-146.

Cronin, J. B., McNair, P. J. & Marshall, R. N. 2000. The role of maximal strength and load on initial power production. Med Sci Sports Exerc. 32(10): 1763-1769.

Cronin, J. B., McNair, P. J. & Marshall, R. N. 2001. Developing explosive power: comparison of technique and training. J Sci Med Sport. 4: 59-70

Doss, W. S. & Karpovich, P. V. 1965. A comparison of concentric, eccentric and isometric strength of elbow flexors. J. Appl. Physiol. 20: 351–353, 1965.

Dudley, G. A., Tesch, P. A., Miller, B. J. & Buchanan, P. 1991. Importance of eccentric actions in performance adaptations to resistance training. Aviat Space Environ Med. 1991 Jun;62(6):543-50.

Duhig, S. J., Bourne, M. N., Buhmann, R. L., Williams, M. D., Minett, G. M., Roberts, L. A., Timmins, R. G., Sims, C. K. E. & Shield, A. J. 2019. Effect of concentric and eccentric hamstring training on sprint recovery, strength and muscle architecture in inexperienced athletes. Journal of Science and Medicine in Sport. 22: 769-774.

Duncan, P. W., Chandler, J. M., Cavanaugh, D. K., Johnson, K. R. & Buehler, A. G. 1989. Mode and speed specificity of eccentric and concentric exercise training. J. Orthop. Sports Phys. Ther. 1989;11(2):70-5.

Ellenbecker, T. S., G. J. Davies, and M. J. Rowinski. Concentric versus eccentric isokinetic strengthening of the rotator cuff: objective data versus functional test. Am. J. Sports Med. 16: 64–69, 1988

Elmer, S, Hahn, S, McAllister, P, Leong, C, and Martin, J. 2012. Improvements in multi-joint leg function following chronic eccentric exercise. Scand J Med Sci Sports. 22: 653-661.

Eltman, J. G. M., Sargeant, A. J., van Mechelen, W. & de Haan, A. 2004. Voluntary activation level and muscle fiber recruitment of human quadriceps during lengthening contractions. Journal of Applied Physiology. 97: 619-626.

Farup, J. Rahbek, S. K, Reis, S., Vendelbo, M. H., de Paoli, F. & Vissing, K. 2014a. Influence of exercise contraction mode and protein supplementation on human skeletal satellite cell content and muscle fiber growth. J Appl Physiol. 117: 898-909.

Farup, J. Rahbek, S. K, Reis, S., Vendelbo, M. H., Bejder, A. & Ringgard, S. 2014b. Whey protein supplementation accelerates satellite cell proliferation during recovery from eccentric exercise. Scand J Med Sci Sports. 24: 788–798.

Farthing, J. P. & Chilibeck, P. D. 2003. The effects of eccentric and concentric training at different velocities on muscle hypertrophy. Eur J Appl Physiol. 89: 578–586.

Fioranelli, D. & Lee, C. M. 2008. The influence of bar diameter on neuromuscular strength and activation: inferences from an isometric unilateral bench press. Journal of Strnegth and Conditioning Research. 2(3): /661–666.

Franchi, M. V., Atherton, P. J., Reeves, N. D., Flück, M., Williams, J., Mitchell, W. K., Selby, A., Valls, R. M. B. & Narici, M. V. 2014. Architectural, functional and molecular responses to concentric and eccentric loading in human muscle. Acta Physiol. 210. 642-654.

Green, H. J., Daub, B., Houston, M. E., Thomson, J. A., Frase, I. & Ranney, D. 1981. Human vastus lateralis and gastrocnemius muscles: A comparative histocemichal and biocemichal analysis. Journal of Neurological Sciences. 52. 201-210.

Gross, M., Lüthy, F., Kroell, J., Müller, E., Hoppeler, H & Vogt, M. 2010. Effects of Eccentric Cycle Ergometry in Alpine Skiers. Int J Sports Med. 31: 572-576.

Hawkins, S. A., Schroeder, E. T., Wiswell, R. A., Jaque, S. V., Marcell, T. J. & Costa, K. 1999. Eccentric muscle action increases site-specific osteogenic response. Med. Sci. Sports Exerc. 31: 1287-1292.

Higbie, E. J., Cuerton, K. J., Warren III, G. L. & Prior, B. M. 1996. Effects of concentric and eccentric training on muscle strength, cross-sectional area, and neural activation. J. Appl. Physiol. 81(5): 2173–2181.

Holliander, D. B., Kraemer, R. R., Kilpatrick, M. W., Ramadan, Z. G., Reeves, G., V., Francois, M., Hebert, E. P. & Tryniecki, J. L. 2007. Maximal Eccentric and Concentric Strength Discrepancies Between Young Men and Women for Dynamic Resistance Exercise. J Strength Cond Res. 21(1): 34-40.

Housh, T. J., Housh, D. J., Weir, J. P. & Weir, L. L. 1996. Effects of eccentric-only resistance training and detraining. Int J Sports Med. 17: 145-148.

Hortobagyi, T., Dempsey, L., Fraser, D., Zheng, D., Hamilton, G., Lambert, J & Dohm, L. 2000. Changes in muscle strength, muscle fiber size and myofibrillar gene expression after immobilization and retraining in humans. Journal of Physiology. 524. 293-304.

Häkkinen, K. & Komi, P. V. Electromyographic changes strength training and detraining. 1983. Medicine and Science in Sports and Exercise. 15(6): 455-460.

Ikegawa, S., Funato, K., Tsunoda, N., Kanehisa, H., Fukunaga, T. & Kawakami, Y. 2008. Muscle force per cross-sectional area is inversely related with pennation angle in strength tained athletes. Journal of Strength and Conditioning Research. 22(1): 128-131.

Johnson, B. L. Adamczyk, J. W., Tennoe, K. O. & Stromme, S. B. 1976. A comparison of concentric and eccentric muscle training. Medicine and science in sports. 8(1), 35-38.

Jones, D. A. & Rutheford, O. M. 1987. Human muscle strength training: The effects of three regimes and the nature of the resultant changes. J. Physiol. 391. 1-11.

Jung, D-H., Lee, W-H., Kim, S-J. & Cynn, H-S. 2011. Correlations Between Maximal Isometric Strength and the Cross-Sectional Area of Lumbrical Muscles in the Hand. Physical Therapy Korea. 18(4), 31-38.

Kaminski, T. W., Wabbersen, C. V. & Murphy, R. M. 1996. Concentric versus enchanced eccentric hamstring strength training: Clinical implications. Journal of Athletic Training. 33(3): 216-221.

Kim, S. Y., Ko, J. B., Farthing, J. P. & Butcher, S. J. 2015. Investigation of supraspinatus muscle architecture following concentric and eccentric training. Journal of Science and Medicine in Sport. 18(4): 378-382.

Lieber, R. L. & Ward, S. R. 2011. Skeletal muscle design to meet functional demands. Phil. Trans. R. Soc. B. 366: 1466-1476.

Mannheimer, J. S. 1968. A Comparison of Strengt Gain Between Concentric and Eccentric Contractions. Physical Therapy Section. 49: 1201-1207.

Maughan, R. J., Watson, J. S. & Weir, J. 1984. Muscle strength and cross-sectional area in man: A comparison of strength-trained and untrained subjects. Brit. J. Sports Med. 18(3): 149-157.

Miller, R. M., Freita, E. D., Heishman, A. D., Kaur, J., Koziol, K. J., Galletti, B. A. & Bemben, M. G. 2019. Maximal power production as a function of sex and training status. Biology of Sport. 36(1):31-37.

Mjolsnes, R., Arnason, A., Østhagen, T., Raastad, T. & Bahr, R. A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. Scand J Med Sci Sports. 14: 311-317.

Moore, D. R., Young, M & Phillips, S. M. 2012. Similar increases in muscle size and strength in young men after training with maximal shortening or lengthening contractions when matched for total work. Eur J Appl Physiol. 112: 1587-1592.

Moore, D. R., Phillips, S. M., Babraj, J. A., Smith, K. & Rennie, M. J. 2005. Myofibrillar and collagen protein synthesis in human skeletal muscle in young men after maximal shortening and lengthening contractions. Am J Physiol Endocrionl Metab. 288: 1153-1159.

Moss, B. M., Refsnes, P. E., Abilgaard, A., Nicolaysen, K. & Jensen, J. 1997. Effects of maximal effort strength training with differnet loads on dynamic strength, cross-sectional area, load-power and load-velocity relationships. Eur J Appl Physiol. 75: 193-199.

Naciri, M. V., Roi, G. S., Landoni, L., Minetti, A. E. & Cerretelli, P. 1989. Changes in force, cross-sectional area and neural activation during strength training and detraining of the human quadriceps. European Journal of Applied Physiology and Occupational Physiology. 59(4): 310-319.

Newton, R. U., Murphy, A. J., Humphries, B. J., Wilson, G. J., Kraemer, W. J. & Häkkinen, K. 1997. Influence of load and stretch shortening cycle on the kinematics, kinetics and muscle activation that occurs during explosive upper-body movements. Eur J Appl Physiol. 75: 333-342.

Nicols-Richardson, S. M., Miller, L. E., Wootten, D. E., Ramp, W. K. & Herbert, W. G. 2007. Concentric and eccentric isokinetic resistance training similarly increases muscular strength, fat-free soft tissue mass, and specific bone mineral measurement in young women. Osteoporos Int. 18: 789-796.

Papadopoulos, C., Theodosiou, K., Bogdanis, G. C., Gkantiraga, E., Gissis, I., Sambanis, M., Souglis, A. & Sotiropoulos, A. 2014. Multiarticular isokinetic high-load eccentric training induces large increases in eccentric and concentric strength and jumping performance. J Strength Cond Res 28(9): 2680–2688.

Pérez-Castilla, A., Comfort, P., McMahon, J. J., Pesaña-Melero, F. L. & García-Ramos, A. 2020. Comparison of the force-, velocity- and power-time curves between the concentric-only and eccentric-concentric bench press exercises. J Strength Cond Res. 34(6): 1618-1624.

Pestana-Melero, F. L., Jaric, S., Pérez-Castilla, A.,Rojas, F. J. & Garcia-Ramos, A. 2020. Comparison of mechanical outputs between the traditional and ballistic bench press: role of the type of variable. J Strength Cond Res. 34(8): 2227-2234.

Petterson, S. C., Barrance, P., Marmon, A. R., Handling, T., Buchanan, T. S. & Synder-Mackler, L. 2011. Course of Quad Strength, Area, and Activation after Knee Arthoplasty and strength training. Med. Sci. Sports Exec. 43(2): 225-231.

Pincivero, D. M., Polen, R. R. & Byrd, B. N. 2019. Contraction mode and intensity effects on elbow antagonist muscle co-activation. Journal of Electromyography and Kinesiology. 44: 101-107.

Pinto R.S., Cadore E.L., Correa C.S., Cordeiro da Silva B.G., Alberton C.L., Lima C.S. & Carlos de Moraes A. 2013. Relationship between workload and neuromuscular activity in the bench press exercise. Med Sport. 17(1): 1-6.

Plas, R. L. C., Degens, H., Meijer, J. P., de Wit, G. M. J., Philippens, I. H. C. H. M., Bobbert, M. F. & Jaspers, R. T. 2015. Muscle contractile properties as an explanation of the higher mean power output in marmosets than humans during jumping. The Journal of Experimental Biology. 218: 2166-2173.

Potier, T., Alexander, C. M. & Seynnes, O. R. 2009. Effects of eccentric strength training on biceps femoris muscle architecture and knee joint range of movement. Eur J Appl Physiol. 105: 939-944.

Pritchard, H. J., P. W. Fink & S. R. Stannard. 2015. The effects of concentric/eccentric training versus concentric only training on peak power and functional muscle performance. Journal of Australian Strength and Conditioning. 23(6): 71-75.

Raue, U., Terpstra, B., Gallagher, P. M. & Trappe, S. W. 2005. Effects of Short-Term Concentric vs. Eccentric Resistance training on Single Muscle Fiber MHC Distribution in Humans. Int J Sports Med. 26: 339-343.

Roig, M., O'Brien, K. Kirk, G., Murray, R., McKinnon, P, Shadgan, B & Reid, W. D. 2008. The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: a systematic review with meta-analysis. Br J Sports Med. 43:556-568.

Schoenfeld, B. J, Ogborn, D. I., Vigotsky, A. D., Franchi, M. V. & Krieger, J. W. 2017. Hypertrophic effects of concentric vs. eccentric muscle actions: A systematic review and meta-analysis. Journal of Strength and conditioning research. 31:2599-2608.

Seger, J. Y., Arvidsson, B. & Thorstensson, A. 1998. Specific effects of eccentric and concentric training on muscle strength and morphology in humans. Eur J Appl Physiol. 79: 49-57.

Seger, J. Y. & Thornstesson, A. 2005. Effects of eccentric versus concentric training on thigh muscle strength and EMG. Int J Sports Med. 26(1): 45-52.

Sheppard, J., Hobson, S., Barker, M., Taylor, K., Chapman, D., McGuigan, M. & Newton, R. 2008. The Effect of Training with Accentuated Eccentric Load Counter-Movement Jumps on Strength and Power Characteristics of High-Performance Volleyball Players. International Journal of Sports Science & Coaching. 3: 355- 363.

Sheppard, J. M., Chapman, D. & Taylor K-L. 2011. An evaluation of a strength qualities assessment method for the lower body. Journal of Australian Strength and Conditioning. 19(2): 4-10.

Shield, A. & Zhou, S. 2004. Assessing voluntary muscle activation with the twitch interpolation technique. Sports Med. 34(4): 253-267.

Stasinaki, A-N., Zaras, N., Methenitis, S., Bogdanis, G. & Terzis, G. 2019. Rate of force development and muscle architecture after fast and slow velocity eccentric training. Sports. 7: 41-52.

Strasser, E. M., Draskovits, T., Praschak, M., Quittan, M. & Graf, A. 2013. Association between ultrasound measurements of muscle thickness, pennation angle, echogenicity and skeletal muscle strength in the elderly. American Aging Association. 35: 2377-2388.

Thomas, C., Jones, P. A. & Comfort, P. 2015. Reliability of the Dynamic Strength Index in College Athletes. International Journal of Sports Physiology and Performance.10: 542-545.

Timmins, R. G., Ruddy, J. D., Presland, J., Maniar, N., Shield, A. J., Williams, M. D. & Opar, D. A. 2016. Architectural changes of the biceps femoris long head after concentric and eccentric training. Med Sci Sports Exerc. 48: 499-508.

Vikne, H., Refnes, P. E., Ekmark, M., Medbo, J. I., Gundersen, V. & Gundersen, K. 2006. Muscular performance after concentric and eccentric exercise in trained men. Med Sci Sports Exerc. 38: 1770-1781.

Westing, S. H., Cresswell, A. G. & Thorstensson, A. 1991. Muscle activity during maximal voluntary eccentric and concentric knee extension. European Journal of Applied Physiology and Occupational Physiology. 62(2): 104-108.

Young, K. P., Haff, G. G., Newton, R. U. & Sheppard, J. M. 2014. Reliability of a Novel Testing Protocol to Assess Ypper-Body Strength Qualities in Elite Athletes. International Journal of Sports Physiology and Performance. 9:871-875.

Young, K. P., Haff, G. G., Newton, R. U., Gabbett, T. J. & Sheppard, J. M. 2015. Assessment and Monitoring of Ballistic and Maximal Upper-Body Strength Qualities in Athletes. International Journal of Sports Physiology and Performance. 10: 232-237.