Brief Review: Effects of Isometric Strength Training on Strength and Dynamic Performance

Authors
Danny Lum[1, 2], Tiago M. Barbosa[3, 4]

Affiliations
1 Singapore Sport Institute, Sport Science and Medicine Centre, Singapore, Singapore
2 Physical Education and Sports Science, National Institute of Education, Nanyang Technological University, Singapore, Singapore
3 Physical Education & Sports Science Academic Group, National Institute of Education, Nanyang Technological University, Singapore, Singapore
4 Polytechninc Institute of Braganca, Portugal

Key words
musculotendinous stiffness, rate of force development, muscle hypertrophy, joint angle, static strength training

accepted 16.02.2019

Bibliography
DOI https://doi.org/10.1055/a-0863-4539
Published online: 2019
Int J Sports Med

ISSN 0172-4622

Correspondence
Mr. Danny Lum, MSc
Exercise and Sports Studies
Singapore Sport Institute,
Sport Science and Medicine Centre,
3 Stadium Drive,
Singapore 397630
Singapore
Tel.: + 65/9729/0 819, Fax: + 65/6440/9 205
dannylum82@gmail.com

ABSTRACT

This review used a narrative summary of findings from studies that focused on isometric strength training (IST), covering the training considerations that affect strength adaptations and its effects on sports related dynamic performances. IST has been shown to induce less fatigue and resulted in superior joint angle specific strength than dynamic strength training, and benefited sports related dynamic performances such as running, jumping and cycling. IST may be included into athletes' training regime to avoid getting overly fatigue while still acquiring positive neuromuscular adaptations; to improve the strength at a biomechanically disadvantaged joint position of a specific movement; to improve sports specific movements that require mainly isometric contraction; and when athletes have limited mobility due to injuries. To increase muscle hypertrophy, IST should be performed at 70–75 % of maximum voluntary contraction (MVC) with sustained contraction of 3–30 s per repetition, and total contraction duration of > 80–150 s per session for > 36 sessions. To increase maximum strength, IST should be performed at 80–100 % MVC with sustained contraction of 1–5 s, and total contraction time of 30–90 s per session, while adopting multiple joint angles or targeted joint angle. Performing IST in a ballistic manner can maximize the improvement of rate of force development.

Introduction

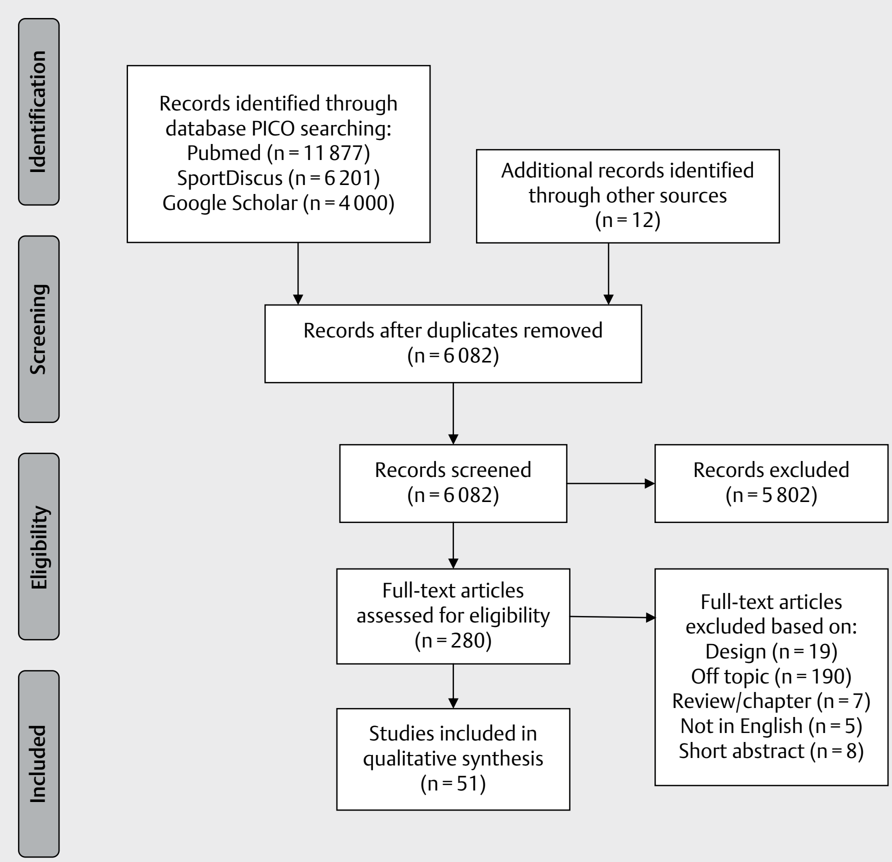
Dynamic strength training is the preferred mode of strength training as strength gained via this method is able to translate to better sports related dynamic performance [61]. In contrast, isometric strength training (IST), a mode of strength training that involves contraction of the skeletal muscles without any external movement, is believed to be less relevant to sports performance due to the static nature of the training method. Despite this believe, IST has been shown to be effective in improving isometric force production at the joint angle that the muscles were trained at [30, 66], as well as joint angles that were not included in the training intervention [8, 50]. Additionally, studies on IST have also shown positive effects on dynamic strength [8, 13, 19, 31, 63, 69], jump performances [10, 11, 21, 33, 36], various sports related dynamic performances including running [2, 18], cycling [73], soccer related skills [10], Muay Thai strike [38] and bouldering grip [39], injury and pain management [17, 22, 42] and tendon properties [12, 32, 35, 36].

The energy demand of isometric muscle contraction has been shown to be lower than that of dynamic muscle contraction [1, 9, 49]. This suggests that performing IST might result in lower level of fatigue than dynamic strength training. Therefore, isometric exercises may be used to replace some dynamic exercises in a training program for athletes to reduce the risk over fatigue. In addition, as IST has been shown to be effective in increasing maximum strength at the joint angle that was adopted during training [26, 30, 35, 66, 69], and is also shown to be superior at increasing angle specific strength as compared to dynamic strength training [19, 26, 27, 32, 37, 47], athletes may adopt IST when they want to improve their force production specifically at the most biomechanically disadvantage joint position of a particular movement. Moreover, it has been shown that running economy can be improved by performing either IST [18] and dynamic strength training [7, 48]. Furthermore, although dynamic strength measures have been shown to be highly correlated to sports-related dynamic performance such as sprinting and jumping [52, 60], studies have also shown similar findings for isometric strength measures (peak force, rate of force development (RFD), impulse) [45, 46, 54, 59].

Although a large number of studies on IST are available in the literature, there is currently no review on the body of knowledge. A variety of IST methods have been studied and resulted in different adaptations. It is important for practitioners to consider the available information in the literature in order to plan the best training program to enhance sports performance. Therefore, the purpose of this narrative review paper is to explore the benefits of different methods of IST on muscular hypertrophy and strength, and sports related dynamic performance, provide recommendations to practitioners for prescribing isometric exercises and to provide information on the current gaps in the literature.

Materials and Methods

▶ **Fig. 1** illustrates the summary of the literature search process. Original and review journal articles were searched and retrieved from electronic searches on Pubmed, SPORTDiscus and Google Scholar databases, with no restriction on language and limits on year of publication. The search strategy included the search terms "isometric strength training", "resistance training", "maximum voluntary contraction" and "modes of strength training". Reference lists of the included studies were reviewed for additional publications. The Boolean search string is as follows: ("human" OR "subject" OR "participant" OR "male" OR "female") AND ("isometric strength training" OR "resistance training" OR "modes of strength training") AND ("RCT" OR "randomized controlled trial" OR "crossover" OR "comparison") AND ("sports performance" OR "strength" OR "force" OR "hypertrophy" OR "power" OR "torque" OR "height" OR "RFD" OR "rate of force development" OR "jump" OR "run" OR "cycling" OR "swim").



▶ **Fig. 1** Summary of search strategy.

A total of 6086 studies were retrieved excluding duplicates. The included studies were original research papers that focused on IST intervention alone or in comparisons with other modes of strength training, in human subjects. 6036 studies on, strength training that did not involve IST, isometric strength test, effects of IST on cardiovascular adaptations or pain management but no neuromuscular adaptations reported, acute effect IST, effects of IST on animal subjects, not written in English and not published in peer reviewed journals, were excluded. Remaining 51 papers have been read in full and included. The review was conducted in accordance to the International Journal of Sports Medicine ethical standards in sport ad exercise science research [24].

Results

Fifty-one papers have been included in the review (▶ **Table 1**). Twenty-six papers addressed the dose-response to isometric strength training (26 on volume and intensity and 3 on rate of force development). Thirteen papers are about the influence of joint position on adaptations to isometric strength training (8 addressing the training at short vs. long muscle length, 5 training at multiple joint angles). The effects of isometric strength training on sports relate dynamic performance is covered by 15 papers retrieved (8 on jumping, 2 on running, 1 on cycling 1 on soccer skills and 2 on other sports skills). Four papers covered more than one variable.

Discussion

Dose-response to isometric strength training

Volume and intensity

It has been shown that 42–100 days of IST training resulted in 5.4–23 % increase in muscle cross-sectional area accompanied by up to 91.7 % increase in strength [5, 14, 20, 25, 26, 28, 35, 50, 51, 58]. The magnitude of muscle hypertrophy from each study was associated with the duration of the intervention training, with a longer intervention period showing higher magnitude of muscle hypertrophy. Other factors affecting the magnitude of hypertrophy included training intensity and volume, contraction duration and muscle length at which isometric contraction occurred during training. Collectively, it has been shown that IST which required participants to sustain contraction for > 3 s resulted in greater amount of muscle hypertrophy as compared to the protocols which only required sustaining contraction for 1–3 s, even when volume and intensity of training were equalized [58]. In one study, Schott et al. [58] found that the protocol involving longer sustained contraction (4 × 30 s) as compared to the shorter sustained contraction (4 × 10 × 3 s), led to significantly greater improvement in isometric strength (54.7 vs. 31.5 %) and hypertrophy (10.1–11.1 vs. 4.3–6.5 %), even when intensities of both protocols were kept the same. The authors suggested that the higher metabolites concentration and lower muscle pH during the longer sustained contraction protocol was most likely the reason for the increase muscle hypertrophy. However, Kubo et al. [34] who compared 2 methods of isometric leg extension training protocol, 3 × 50 repetitions of non-sustained contraction vs. 4 × 20 s sustained contraction, at 70 % MVC for a total of 50 training sessions, found similar magnitude of muscle hypertrophy (7.4 vs. 7.6 %) and strength gain (31.8 vs. 33.9 %) in both protocols. The difference in findings on muscle hypertrophy could be due to the difference in method of measuring muscle hypertrophy. Schott et al. [58] measured muscle size using computer tomographic scans at one- and 3-quarter of femur length, while Kubo et al. [34] measured muscle cross sectional area using magnetic resonance imaging. Possible reason for the conflicting findings in isometric strength improvement could be because Schott et al. [58] equalized the training volume between the 2 protocols while Kubo et al. [34] did not. In fact, the non-sustained contraction protocol in the study by Kubo et al. [34] induced a greater total contraction duration than the sustained contraction protocol (150 vs. 80 s). This indicates that when intensity of training is equalised, the magnitude of strength and hypertrophy gained could more likely to be determined by the total contraction duration per training session rather than per repetition. This was evident in the study by Balshaw et al. [5] which required one group of participants to perform 4 × 10 × 3 s (total of 120 s) isometric leg extension at 75 % MVC for 36 training sessions. The results showed an 8 % increase in muscle cross-sectional area in the participants. This magnitude of hypertrophy is comparable to that found in both Schott et al. [58] and Kubo et al. [34].

An early study by Young et al. [72] compared the effects of IST using a sustained contraction protocol which involved isometric contraction for 1 min at 30 % MVC and rhythmic protocol which involved 100 % MVC without sustaining contraction. The results showed that the rhythmic protocol was more effective in increasing muscular strength (5.5 % per week vs. 3.3 % per week) while the sustained contraction protocol was superior in improving muscular endurance. The finding of this study suggested that exercising at or near maximal intensity was superior in inducing maximal strength improvement while exercising at submaximal load with increased time under tension was more beneficial in improving muscular endurance. This was supported by Khouw and Herbert [29], who also showed greater increase in strength after performing IST at nearer to maximal intensity, but not supported by others [5, 28, 65]. In another study, Hagberg et al. [22] compared a 4 × 2 min (20–30 % MVC) and 10 × 5 s (MVC) isometric shoulder flexion protocol and noted higher strength improvement (5.28 vs. 2.66 Nm) after training at maximal intensity as compared to low intensity but no difference in improvement in muscular endurance. This difference in findings from Young et al. [72] might be because participants were required to sustain contraction at MVC for a period of 5 s in the study by Hagberg et al. [22] while there was no requirement to sustain contraction in the rhythmic protocol in the study by Young et al. [72]. Balshaw et al. [5] and Tillin and Folland [65] reported a sustained contraction protocol involving 3 s isometric contractions at 75 % MVC resulted in greater strength improvement than a protocol involving 1 s isometric ballistic contraction at 80–90 % MVC. Balshaw et al. [5] stated that loading magnitude rather than loading duration accounted for majority of the strength gain. However, greater strength gain was observed in the sustained contraction protocol because of the greater time under tension despite a similar loading intensity (120 s at 75 % MVC vs. 40 s at 80–90 % MVC). This resulted in a significant level of muscle hypertrophy, which was not observed in the ballistic protocol. The

▶ **Table 1** Effects of isometric strength training.

Authors	Participants	Training Intervention	Results
Albracht & Arampatzis [2]	26 recreational long distance runners (Control vs. Exercise)	4 sessions/week for 14 weeks Exercise: 5 × 4 × 3 s MVC isometric plantar flexion at 5° dorsiflexion, 40° hip flexion and full knee extension.	Exercise: Decrease oxygen consumption at 3 m.s^{-1} (5.0 %) and 3.5 m.s^{-1} (3.4 %) running speed; decrease energy cost of running at 3 m.s^{-1} (4.7 %) and 3.5 m.s^{-1} (3.5 %) running speed; increase maximal plantar flexion moment (6.7 %), increase maximal Achilles tendon force (7.0 %), increase tendon aponeurosis stiffness (15.8 %).
Alegre et al. [3]	29 adults (7 females & 22 males) Control vs. K90 vs. K50	2–3 sessions/week for 8 weeks K90: 3–4 × 5–7 × 5 s 60–80 % MVC knee extension at 90° knee angle (0° = full extension). K50: 3–4 × 5–7 × 5 s 60–80 % MVC knee extension at 50° knee angle.	K50: No significant change in isokinetic peak torque (8.2 %); increase muscle thickness (5.2–9.0 %); increase EMG activity; decrease in optimum angle. K90: Increase in isokinetic peak torque (22.6 %); increase muscle thickness (9.0–13.5 %); increase in optimum angle.
Ball et al. [4]	63 male adults Control vs. Experimental	Experimental: 3 sessions/week for 6 weeks 1 × 10 s MVC isometric squat	Experimental: Increase in strength (17.3 %); non-significant increase in jump height (2.3 %).
Balshaw et al. [5]	48 male adults Control vs. Explosive Contraction (ECT) vs. Sustained Contraction (SCT)	3 sessions/week for 12 weeks ECT: 4 × 10 explosive isometric leg extension. SCT: 4 × 10 × 3 s 75 % MVT isometric leg extension.	SCT: Increase in MVT (23 %); increase in torque at 150 ms (12 %); increase EMG activity at MVT & 0–150 ms (33 % & 18 %, respectively); increase hypertrophy (8 %). ECT: Increase MVT (17 %); increase in torque at 50, 100 & 150 ms (34 %, 17 % & 18 %, respectively); increase EMG activity at MVT, 0–50 ms, 0–100ms & 0–150 ms (18 %, 23 %, 17 % & 28 %, respectively); non-significant hypertrophy (2.6 %).
Behm & Sale [8]	16 adults (8 females and 8 males) Isometric vs. Isokinetic foot (Intra-individual comparison)	3 sessions/week for 16 weeks Isometric: 3–5 × 1 s 10 MVC isometric dorsiflexion at 30° plantar flexion angle. Isokinetic: 3–5 × 10 isokinetic dorsi flexion at 5.23 rad/s.	Isometric: Increase in isokinetic torque (~35 %). Isokinetic: Increase in isokinetic torque (~25 %).
Bimson et al. [10]	16 female amateur soccer players Control vs. Experimental	Experimental: Once per week IST for 6 weeks. 1 × 3 s maximal isometric leg extension at multiple knee angles.	Experimental: Increase in CMJ height (2.24 %) and kicking distance (8.8 %).
Bogdanis et al. [11]	15 male university students 85° vs. 145° knee angle	3 sessions/week for 6 weeks 85°: 5–7 × 3 s MVC isometric leg press at 85° knee angle 145°: 5–7 × 3 s MVC isometric leg press at 145° knee angle Both groups performed countermovement jumps during rest interval.	85°: Increased in maximal isometric force (13.4 %) and vertical jump height (8.1 %). 145°: Increased vertical jump height (7.4 %).
Burgess et al. [12]	13 male adults Plyometric vs. Isometric	2–3 sessions/week for 6 weeks Plyometric: 3–4 × 15–20 one-legged straight leg drop jump. Isometric: 3–4 × 1 s 15–20 one-legged explosive isometric plantar flexion.	Plyometric: Increase in tendon stiffness (29.4 %), jump height (58.6 %) and RFD (18.9 %). Isometric: Increase tendon stiffness (61.6 %) and RFD (16.7 %). Non-significant increase in jump height (64.3 %).
Chui [13]	96 male university students Control vs. Isometric vs. Rapid Contraction vs. Slow Contraction	3 sessions/week for 9 weeks All groups performed the following 6 exercises: 2-hand military press, stiff-leg deadlift, 2-hand curl, squat, supine press & sit up. Isometric: 3 × 6 s mid-range isometric contraction at 10 RM load. Rapid Contraction: 3 × 10 rapid dynamic contractions at 10 RM. Slow Contraction: 3 × 10 slow dynamic contraction at 10 RM.	Significant increase in strength for elbow flexion & extension, shoulder vertical & horizontal flexion, hip & knee extension, trunk flexion & extension, in all training groups. Significant improvements in speed of movement with and without resistance for press, curl, supine press, stiff-leg deadlift, squat and sit up in all training groups.
Davies et al. [14]	6 female and 6 male adults Trained vs. Control arm	Trained: 3 sessions/week for 6 weeks 4 × 6 × 4 s isometric single arm elbow flexion at 80 % MVC.	Trained: Increase in isometric force (14.5 %) and CSA (5.4 %).
Ebersole et al. [16]	17 female adults Control vs. Training	3 sessions/week for 8 weeks Training: 3–5 × 6 s 80 % MVC isometric arm flexion at arm 60° elbow flexion.	Training: Increased in isometric torque at 30°, 60° & 90° elbow angles (19.7 %, 21.8 % & 8.2 %, respectively) and arm circumference (2.2 %)
Fisher et al. [17]	15 male adults with knee osteoarthritis (All subjects performed combine isometric & isotonic training)	3 sessions/week for 16 weeks Isometric: 2–5 × maximum duration MVC isometric knee extension at multiple knee and hip angles. Isotonic: 3–5 × isotonic knee extension at with intensity equivalent to 10–50 % of MVC.	Increased in strength (23–47 %), endurance (10–56 %) and angular velocity (15–35 %).

▶ **Table 1** Continued

Authors	Participants	Training Intervention	Results
Fletcher et al. [18]	6 highly-trained male endurance runners	3 sessions/week for 8 weeks 4×20 s isometric plantarflexion at 80% peak force.	Significant increase in peak force (36%), muscle tendon unit stiffness (41%), and running economy at 95% of lactate threshold (7%).
Folland et al. [19]	33 male adults Isometric training leg vs. Dynamic training leg	3 sessions/week for 9 weeks Isometric: 4×10×2 s single leg isometric leg extension at multiple knee angles, and 75% of maximum isometric contraction. Dynamic: 4×10 variable resistance leg extensions at 75% of maximum load.	Isometric: Increased isometric strength at 4 knee angles (18%) and isokinetic strength at 3 velocities (10.5%). Dynamic: Increased isometric strength at 4 knee angles (13.1%) and isokinetic strength at 3 velocities (10.7%).
Garfinkel & Cafarelli [20]	15 sedentary female university students Control vs. Experimental	Experimental: 3 sessions/week for 8 weeks 3×10×3–5 s single leg isometric leg extension at MVC.	Experimental: Significant increase in MVC (28%) and muscle CSA (14.6%).
Goldmann et al. [21]	27 healthy male adults Control vs. Experimental	Experimental: 4 sessions/week for 7 weeks 4×5×3 s isometric toe flexion at 90% MVC.	Experimental: Significant increase in toe flexion (66.7–80.9%) and ankle plantarflexion (8.7%) MVC and horizontal jump distance (2.7%).
Hagberg et al. [22]	69 female adults with shoulder and neck injuries. Endurance vs. Strength	3 sessions/week for 12 weeks Endurance: 4×2 min 90° isometric shoulder flexion that corresponded to 20–30% maximum shoulder joint torque. Strength: 10×5 s 90° isometric shoulder flexion at maximal contraction.	Strength: Increased in shoulder abduction (19.3–20.9%), flexion (17.2–19.6%) and outward rotation strength (9.1–11.1%) and grip strength (10.2–18.6%). Endurance: Increased in shoulder abduction (9.8–13.9%), flexion (11.5–15.1%) and outward rotation strength (7.5–9.0%) and grip strength (4.3–5.1%).
Ikai & Fukunaga [25]	6 male adults Trained vs. Untrained arm	6 sessions/week for 100 days Trained: 3×10 s MVC isometric arm flexion.	Trained: Increased in maximum strength (91.7%) and muscle CSA (23%).
Jones & Rutherford [26]	1 female and 11 male adults Control vs. Isometric vs. Concentric vs. Eccentric leg	3 sessions/week for 12 weeks Isometric: 4×6×4 s single leg isometric leg extension at 80% MVC. Concentric: 4×6 single leg concentric only leg extension at 80% maximum load. Eccentric: 4×6 single leg eccentric only leg extension at 80% maximum load.	Isometric: Increase in isometric force (34.2%) and muscle CSA (4.8%). Concentric: Increase in isometric force (15.4%) and muscle CSA (5.7%). Eccentric: Increase in isometric force (10.8%) and muscle CSA (3.5%).
Kanehisa & Miyashita [27]	20 male adults Isometric Fast (FG) vs. Isometric Slow (SG)	Same isometric training for 5 sessions/week for 8 weeks. Isokinetic training for 5 sessions/week for subsequent 6 weeks Isometric: 3×5 s maximal isometric elbow flexion at multiple elbow angles. FG: 29×maximal isokinetic elbow flexion at 157°/s. SG: 13×maximal isokinetic elbow flexion at 73°/s	Isometric: Increased isometric strength at 4 joint angles (27–36%), power at 4 intensity levels (34–46%), and arm circumference (1.8%). FG: Increase in power while lifting light loads (9.4–15.5%). SG: Increase in power while lifting heaviest load (13.1%).
Kanehisa et al. [28]	12 male adults 100% vs. 60% group	3 sessions/week for 10 weeks 100%: 12×6 s MVC single arm isometric elbow extension at 1.57 rad elbow angle. 60%: 4×30 s 60% MVC single arm isometric elbow extension at 1.57 rad elbow angle.	100%: Increase in muscle volume (12.4%), fascicle angle (16%), isometric torque (53.2%) and concentric & eccentric torque (14–49%). 60%: Increase in muscle volume (5.3%), fascicle angle (15%), isometric torque (60.2%) and concentric & eccentric torque (19–40%).
Khouw & Herbert [29]	51 university students (33 females & 18 males) Trained vs. Untrained arm	3 sessions/week for 6 weeks 6×10 s isometric elbow flexion at 140° elbow angle. Each subject trained at different intensity between 0–100% MVC.	Subjects who trained near 0% MVC: Increase MVC (~5.3%) Subjects who trained near 100% MVC: Increase MVC (~24.3%)
Kitai & Sale [30]	6 female adults Control vs. Training leg	Training: 3 sessions/week for 6 weeks 2×10×5 s maximal isometric plantarflexion at 0° plantar flexion angle.	Training: Increase in strength at 0° (18%), 5° plantar- (16.8%) and 5° dorsiflexion (13.6%), twitch torque (12.3%), calf circumference (1.1%).
Knapik et al. [31]	6 female and 6 male adults Isometric vs. Isokinetic	3 sessions/week for 10 weeks Isometric: 50×3 s 80% MVC isometric elbow extension at 90° elbow angle. Isokinetic: 50×80% maximum isokinetic elbow extension.	Isometric: Increase in isometric strength at 3 joint angles (~50%) and isokinetic strength (~33%). Isokinetic: Increase in isometric strength at 3 joint angles (~80%) and isokinetic strength (~88%).
Kubo et al. [32]	10 male adults Static vs. Dynamic training leg (Intra-individual comparison)	4 sessions/week for 12 weeks Static: 10×15 s×70% MVC single leg isometric knee extension at 90° knee flexion angle. Dynamic: 5×10 single leg dynamic knee extension at 80% 1RM.	Static: Increase in MVC (49%), neural activation (9.5%), muscle volume (4.5%), stiffness of tendon-aponeurosis (55%) and patella tendon (83%). Dynamic: Increase in MVC (32%), neural activation (7.6%), muscle volume (5.6%), stiffness of tendon-aponeurosis (30%).

▶ **Table 1** Continued

Authors	Participants	Training Intervention	Results
Kubo et al. [33]	11 male adults Plyometric vs. Isometric	3 sessions/week for 12 weeks Plyometric: 5 × 10 × hopping & drop jump at 40 % 1RM. Isometric: 10 × 15 s 80 % MVC isometric plantar flexion at neutral joint angle.	Isometric: Increase in MVC (19.7 %), muscle thickness (~5.5 %), ramp (37.1 %) and ballistic stiffness (26 %), concentric angular velocity (9.6 %) and non-countermovement jump height (17 %). Non-significant increase in CMJ height (12.6 %), DJ height (10.7 %) and joint stiffness (11.7 %). Plyometric: Increase in MVC (3.9 %), muscle thickness (~6 %), active muscle stiffness (38–70 %), non-countermovement jump height (52 %), CMJ height (48.2 %), DJ height (39.7 %) and joint stiffness (30 %).
Kubo et al. [34]	8 male adults Shot vs. Long duration contraction (Intra-individual comparison)	4 sessions/week for 12 weeks Short: 3 × 50 × 1 s rapid single leg isometric knee extension at 70 % MVC. Long: 4 × 20 s single leg isometric knee extension at 70 % MVC.	Short: Increase in MVC (31.8 %), muscle volume (7.4 %) and elastic energy (25.7 %). Long: Increase in MVC (33.9 %), muscle volume (7.6 %), tendon stiffness (57.3 %) and elastic energy (12 %).
Kubo et al. [35]	9 male adults Short muscle length (ST) vs. Long muscle length (LT) training leg (Intra-individual comparison)	4 sessions/week for 12 weeks ST: 6 × 15 s 50 %–70 % MVC isometric knee extension at 50° knee flexion. LT: 6 × 15 s 50 %–70 % MVC isometric knee extension at 100° knee flexion.	ST: Increase in MVC at trained angle (49 %) and 40°–80° knee angles and EMG activity (~3–8 %). LT: Increase in MVC at trained angle (44 %) and 40°–120° knee angles, EMG activity (~7–10 %) and stiffness (50.9 %).
Kubo et al. [36]	14 male adults Control vs. Training	Training: 4 sessions/week for 12 weeks 10 × 15 s 70 % MVC isometric leg press	Training: Increase in MVC (12.4 %), stiffness of tendon-aponeurosis (14 %), EMG activity (~3–8 %), SJ height (5 %), duration of push off phase during CMJ (9.4 %) and decrease in knee angular velocity during CMJ (8.6 %)
Lee et al. [37]	31 male adults Isometric (IM) vs. Isotonic (IT) vs. Isokinetic (IK)	3 sessions/week for 8 weeks IM: 10 × 1 s single leg isometric leg extension at multiple knee angles and 75 % maximal voluntary torque. IT: 4 × 10 single leg isotonic leg extension at 75 % of 1 repetition max. IM: 4 × 10 single leg isokinetic leg extension.	IM: Increase in isometric force at 4 knee angles (26.6–34.2 %), 1RM knee extension (19 %), isokinetic torque at 3 angular velocities (11.2–14.2 %) and muscle mass (3.1 %). IT: Increase in isometric force at 4 knee angles (13.4–20 %), 1RM knee extension (36.3 %), isokinetic torque at 3 angular velocities (21.1–26.5 %) and muscle mass (3.9 %). IK: Increase in isometric force at 4 knee angles (12.2–20.9 %), 1RM knee extension (17.9 %), isokinetic torque at 3 angular velocities (22.3–28.6 %) and triple hop distance (4.8 %).
Lee & McGill [38]	12 male Muay Thai athletes Control vs. Dynamic vs. Isometric	4–7 sessions/week for 6 weeks Combination of core muscle exercises changed fortnightly in each group. Dynamic: 5 × 5–10–per exercise. Isometric: 1–5 × 10 s per exercise	Dynamic: Increase strike velocity (13.2–45.5 %) and impact (7.1–18.3 %). Isometric: Increase strike velocity (5.2–23.9 %) and impact (713.1–27 %).
Levernier & Laffaye [39]	14 male elite rock climbers Control vs. Training	Training: 3 sessions/week for 4 weeks 2 × 6 × 4–6 s isometric hold onto rock climbing crimps.	Training: Increase in finger force (5.6–8.8 %) and RFD (26–33.1 %) while gripping various crimps.
Marks [42]	1 male adult with knee osteoarthritis (Case study)	3 sessions/week for 6 weeks 3 × 2 × 5 s MVC isometric knee extension at 60° knee flexion.	Increase in isometric torque at 3 knee angles (25–177 %), improvement in level walking time (7 %) and stair walking time (20 %).
Mauffiu-letti & Martin [44]	21 male adults Control vs. Ballistic vs. Progressive	3 sessions/week for 7 weeks Ballistic: 6 × 6 × 1 s MVC knee extension at 65° knee flexion. Progressive: 6 × 6 × 4 s MVC knee extension at 65° knee flexion.	Ballistic: Increase in MVC (27.4 %), isokinetic torque (18.3 %), peak twitch torque (~30 %), contraction time (~20 %), rate of twitch relaxation (~55 %) and decrease in half relaxation time (~30 %). Progressive: Increase in MVC (15.7 %) and isokinetic torque (15.6 %).
McKethan & Mayhew [47]	24 male adults Control vs. Isometric vs. Isotonic vs. Combined	2 sessions/week for 9 weeks Isometric: 3 × 6 s MVC leg extension at 90°, 110° & 130° knee angle. Isotonic: 3 × 6–10 isotonic leg extension with 6RM load. Combined: 3 × MVC isometric leg extension at 90° knee angle followed by isotonic contraction lasting up to 4 s.	Isometric: Increase in MVC (36.8 %). Non-significant increase in jump height (2.2 %). Isotonic: Increase in MVC (27.8 %). Combined: Increase in MVC (28.5 %). Non-significant increase in jump height (8.1 %).

▶ **Table 1** Continued

Authors	Participants	Training Intervention	Results
Noorkoiv et al. [50]	16 male adults Short muscle length (SL) vs. Long muscle length (LL)	3 sessions/week for 6 weeks SL: 5 × 5 × 5 s MVC knee extension at 30°–50° knee flexion angles (0° is full extension). LL: 5×5×5 s MVC knee extension at 75°–100° knee flexion angles.	SL: Increase in MVC (13.4 %). LL: Increase in doublet force (11.7 %), muscle volume (3.1– − 8.2 %) and voluntary activation (4.8–5.5 %).
Noorkoiv et al. [51]	16 male adults Short muscle length (SL) vs. Long muscle length (LL)	See Noorkoiv et al. [50]	SL: No change in isokinetic torque and muscle volume. LL: Increase in isokinetic torque (10.1–13 %) and muscle volume (4.8–8.2 %).
Pavone & Moffat [54]	31 female adults Concentric vs. Eccentric vs. Isometric	3 sessions/week for 6 weeks Concentric: 3 × 10 concentric knee extension at 50–100 % 10RM load. Eccentric: 3 × 10 eccentric knee extension at 50–100 % 10RM load. Isometric: 3 × 10 × 6 s isometric knee extension at 60° knee angle with 50–100 % 10RM load.	Concentric: Increase in peak torque (22.8 %). Eccentric: Increase in peak torque (18.7 %). Isometric: Increase in peak torque (20.7 %).
Pucci et al. [55]	20 male adults Control vs. Experimental	3 sessions/week for 3 weeks Experimental: 3 × 10 × 3 s MVC isometric knee extension at 90° knee angle.	Experimental: Increase in MVC (35 %) and maximal activation (2.9 %).
Rasch & Pierson [56]	30 adult male Single vs. Multiple joint angles	5 sessions/week for 5 weeks Single: 3 × 15 s elbow flexion at 90° elbow angle. Multiple: 1 × 15 s elbow flexion at 60°, 90° and 120° elbow angles.	Single: Increased MVC at 60°, 90° & 120° elbow angles. Multiple: Increased MVC at 60°, 90° & 120° elbow angles.
Schott et al. [58]	13 adults (10 females and 3 males) Intermittent vs. Continuous contraction (Intra-individual comparison)	3 sessions/week for 14 weeks Intermittent: 4 × 10 × 3 s single leg isometric knee extension at 70 % MVC. Continuous: 4 × 30 s single leg isometric knee extension at 70 % MVC.	Intermittent: Increase in MVC (31.5 %) and isokinetic strength at 2 angular velocities (11.3–11.6 %). Non-significant change in muscle CSA (4.3–6.5 %). Continuous: Increase in MVC (54.7 %) and muscle CSA (10.1–11.1 %).
Symons et al. [63]	37 old adults (19 females & 18 males) Isometric vs. Concentric vs. Eccentric training group	3 sessions/week for 12 weeks Isometric: 3 × 10 × 5 s MVC isometric knee extension at 90° knee angle. Concentric: 3 × 10 × 5 s MVC concentric only isokinetic knee extension at 90°/s. Eccentric: 3 × 10 × 5 s MVC eccentric only isokinetic knee extension at 90°/s.	Isometric: Increase in concentric torque (15.1 %), isometric torque (27.7 %), eccentric torque (16.5 %), peak concentric work (14.9 %) and power (20.8 %) and improved step test time (~7 %). Concentric: Increase in concentric torque (22.1 %), isometric torque (17.3 %), eccentric torque (17.9 %), peak concentric work (45.2 %) and power (51.8 %) and improved step test time (~7 %). Eccentric: Increase in concentric torque (10 %), isometric torque (25.5 %), eccentric torque (26 %), peak concentric work (12.7 %) and power (23.3 %) and improved step test time (~6 %).
Tanaka et al. [64]	16 female adults Control vs. Intervention	Intervention: 3 sessions/ week for 4 weeks 3 × 20 × 3 s 20° isometric plantarflexion at 30 % MVC.	Intervention: Increase in MVC at 0° (29.3 %) and 10° (29 %) plantarflexion.
Tillin & Folland [65]	19 male adults Explosive strength training (EST) vs. Maximal strength training (MST)	4 sessions/week for 4 weeks EST: 4 × 10 explosive isometric leg extension. MST: 4 × 10 × 3 s isometric leg extension at 75 % MVT.	EST: Increase in MVF (10.6 %), force at 50 ms (53.7 %), 100 ms (15 %) & 150 ms (13 %) and EMG activity (~20 %). MVT: Increase in MVF (20.5 %) and EMG activity (~28 %).
Tillin et al. [66]	9 male adults Trained vs. Untrained Leg	4 sessions/week for 4 weeks Trained Leg: 4 × 10 × 3 s single leg isometric leg extension at 75 % MVF.	Trained: Increase in MVF (20 %) and EMG activity (26 %). Untrained: Increase in MVF (8 %).
Tillin et al. [66]	10 male adults Trained vs. Untrained Leg	4 sessions/week for 4 weeks Trained Leg: 4 × 10 explosive isometric leg extension.	Trained: Increase in MVF (10.6 %), voluntary force at 50 ms (54 %), 100 ms (15 %) & 150 ms (7 %), %), octet force at 50 ms (7 %) & 100 ms (10 %) and muscletendinous unit stiffness (34 %).
Ullrich et al. [68]	36 athletes (9 females and 27 males) Isometric vs. Dynamic vs. Combine	2–3 sessions/week for 9 weeks Isometric: 2–7 × 6–10 × 2 s isometric knee extension (90\° knee angle) & flexion (160°–170° knee angle) at 60–80 % MVC. Dynamic: 1–4 × 8–10 dynamic knee extension (80°–115° knee angle) & flexion (170°–135° knee angle) at 40–80 % of 1RM. Combined: Combine Isometric & Dynamic training protocol.	Isometric: Increase in knee extension moment and knee flexion moment at 5 knee angles. Change in optimum knee extension angle. Dynamic: Increase in knee extension moment and knee flexion moment at 5 knee angles. Change in optimum knee extension & knee flexion angles. Combined: Increase in knee extension moment and knee flexion moment at 5 knee angles. Change in optimum knee extension & knee flexion angles.

▸ **Table 1** Continued

Authors	Participants	Training Intervention	Results
Ullrich et al. [69]	36 athletes (9 females and 27 males) Isometric vs. Dynamic vs. Combine	See Ullrich et al. [68]	Isometric: Increase in knee extension peak power at 40 % (20 %) & 60 % (20.3 %) of 1RM and knee flexion peak power at 40 % (47.8 %) & 60 % (25.4 %). Dynamic: Increase in knee extension peak power at 40 % (26.7 %), 60 % (21.2 %) & 80 % (19.4 %) of 1RM and knee flexion peak power at 40 % (53.3 %), 60 % (35 %) & 80 % (19 %). Combined: Increase in knee extension peak power at 40 % (28.1 %) & 60 % (10.3 %) of 1RM and knee flexion peak power at 40 % (29.9 %) & 60 % (13.2 %).
Weir et al. [70]	13 adults (7 females & 6 males) Training vs. Control leg (Intra-individual comparison)	Training: 3 sessions/week for 6 weeks 2 × 10 × 6 s single leg isometric knee extension at 80 % MVC.	Training: Increase in isometric torque at 2 knee angles (22.3–23.3 %).
Weir et al. [71]	17 female college students Control vs. Training	See Weir et al. [70].	Training: Increase in isometric torque at 2 knee angles (7.3 %–27.4 %).
Young et al. [72]	4 male adults Sustained contraction (ST) leg vs. Rhythmic contraction (RT) leg (Intra-individual comparison)	ST: 7 sessions/ week for 8 weeks 7–15 × 1 min single leg isometric ankle flexion at 30 % MVC. RT: 7 sessions/week for 5 weeks Rhythmic single leg isometric ankle flexion at 100 % MVC. Total area under the training force/ time curve was the same as ST.	ST: Increase in MVC (3.3 % per week), and endurance (19.4 %). RT: Increase in MVC (5.5 % per week).
Zoladz et al. [73]	7 male adults (All underwent intervention training)	4 sessions/week for 7 weeks 2 × 5 × 5 s isometric knee extension at MVC, with 30 s rest between repetitions and 3 min rest between sets.	Increase in MVC (19 %), maximal power output during cycling incremental exercise (3.9 %) and reduced oxygen consumption when cycling at below lactate threshold (3.7 %) and above lactate threshold (3.9 %).

CMJ = Countermovement jump; CSA = Cross-sectional area; DJ = Drop jump; ECT = Explosive contraction; EMG = Electromyography; IK = Isokinetic; IM = Isometric; IT = Isotonic; LL & LT = Long muscle length; MVC = Maximal voluntary contraction; MVF = Maximum voluntary force; MVT = Maximal voluntary torque; RT = Rhythmic contraction; SCT = Sustained contraction; SJ = Squat jump; SL & ST = Short muscle length.

addition of muscle hypertrophy was most likely the reason for the greater strength increment in the sustained contraction protocol as compared to the ballistic protocol, which only resulted in strength gain via neural adaptation.

When magnitude of strength gain is compared between the results obtained from different studies, short duration maximal contraction method seems to be a more time efficient method as compared to submaximal contraction method of varying duration. This could be due to greater motor unit recruitment for each repetition in maximal contraction method, resulting in greater strength adaptations [72]. In the study by Pucci et al. [55], participants were required to perform 3 × 10 × 3 s isometric leg extension at MVC for 9 sessions. The results showed a 35 % increase in maximum strength. In another study by Maffiuletti and Martin [44], participants who performed 6 × 6 × 1 s isometric leg extension at MVC over 21 sessions, increased maximum strength by 27.4 %. In comparison to studies by Schott et al. [58], Kubo et al. [34] and Tillin and Folland [65], who showed strength gain of 31.5–54.7 %, 31.8 % and 20.5 %, over 42, 50 and 16 sessions, respectively, the training protocols adopted by Pucci et al. [55] and Maffiuletti and Martin [44] were more time efficient. All these studies recruited healthy adults as participants.

Rate of force development

Although Balshaw et al. [5] and Tillin and Folland [65] showed that sustained contraction resulted in superior maximal strength improvement, the ballistic protocol was shown to be superior in improvement in explosive strength. These studies found that force production in the first 50 and 100 ms improved only after the ballistic protocol. This finding suggested that when the purpose of training is to improve explosive strength, individuals should execute the isometric contraction as fast and as hard as possible. This suggestion was supported by other studies [66, 67] but was not in total agreement with the findings of Maffiuletti and Martin [44]. In this study, participants had to either perform IST with a 4 s build-up to 100 % MVC method or perform the isometric contraction explosively at 100 % MVC. The authors found that there was no significant difference in improvement of maximal isometric force and isokinetic torque (240 °/s) between protocols. Additionally, although the ballistic protocol was prone to increase rate of evoked twitch tension by 4.2 %, it was not statistically significant. The authors suggested that the intensity of contraction, rather than the speed of contraction, was more important in inducing muscular adaptation. Motor unit discharge rate, fibre type, muscle size and tendon stiffness are factors that influences RFD [43]. Most motor units will be recruited during a ballistic contraction even when the force produced is not maximal [43]. However, this is only the case in slow contraction when individuals contract the muscle maximally or to muscular failure during slow contraction [72]. The submaximal contraction in the sustained contraction protocol in Balshaw et al. [5] and Tillin and Folland's [65] study might not have maximally recruited the high threshold units while the 4 s build-up protocol in the study by Maffiuletti and Martin [44] would have. This could be one reason for the difference in findings on explosive strength between the studies. Furthermore, the study by Balshaw et al. [5] and Tillin and Folland [65] determined explosive force production using the isometric force produced in the first 50 and 100 ms while Maffiuletti and Martin [44] determined explosive force using the isokinetic torque performance. The difference in findings could be because the isokinetic test in the study by Maffiuletti & Martin [44] was not performed at a speed that was high enough to detect the difference in the improvement in explosive strength between the 2 protocols.

Current findings suggest that IST performed at 70–75 % of MVC with sustained contraction of 3–30 s per repetition and a total sustained contraction duration of > 80–150 s per session for > 36 sessions is recommended for inducting muscle hypertrophy. While performing IST at 80–100 % MVC with sustained contraction of 1–5 s per repetition, total of 30–90 s per session, is recommended for maximal strength gain. Additionally, IST performed with ballistic contraction to near maximal intensity is recommended for improving explosive strength.

To date, no study has compared the effects of explosive IST with and without sustaining contraction. Additionally, studies comparing the effects of different IST methods were all conducted on healthy male and female adults; none of the studies was conducted on well-trained athletes. Therefore, it is still not known if there would be any difference in neuromuscular adaptations when different IST methods are administered in athletic population.

Influence of joint position on adaptations to isometric strength training

Training at short vs. long muscle length

Muscular force production post-IST tends to increase most at or around the joint angles adopted during the training [8, 16, 30, 31, 35, 50, 70, 71]. Studies on IST have shown that training in one joint angle resulted in strength increment in other joint angles between 20 °–50 ° away from the joint angles adopted during training [31, 64, 68, 70, 71]. These studies have implemented IST at joint angles between 90–135 ° (180 ° = full extension). For example, the study by Ullrich et al. [68] recruited a group of young athletes from various sports to perform 2–7 × 6–10 × 2 s isometric knee extension (90 ° knee angle) & flexion (160–170 ° knee angle) at 60–80 % MVC, 2–3 sessions per week for 9 weeks. The results showed that there was significant increase in knee extension force at 90, 100, 115, 125 and 140 ° knee angles, and knee flexion force at 90 °, 115, 130, 145 and 160 ° knee angles. The increase in knee extension force could have been due to increase in muscle activity [50], increase in muscle hypertrophy [35] or both.

Recent studies have compared the effects of IST at different joint angle or muscle length and found that, performing IST at longer muscle length resulted in greater magnitude in hypertrophy, and strength increment across a larger range of joint angles and movement [3, 11, 35, 50, 51]. In one study, Kubo et al. [35] compared the effects of IST for knee extensor at 80 vs. 130 ° knee angle. The participants had to either perform 6 × 15 s isometric knee extension at either 80 or 130 ° knee angle and 50–70 % MVC, 4 sessions a week for 12 weeks. The results showed that training at 130 ° only increased force production at knee angles between 100–140 °, while training at 80 ° led to increased force production at knee angles between 60–140 °. In addition, the authors also found greater increase in tendon stiffness in the group that performed IST at 80 ° knee angle. This finding was supported by Alegre et al. [3] and Noorkoiv et al. [51], who showed that isokinetic torque was significantly increased in participants who performed IST at longer muscle length and not those who trained at shorter muscle length. However, these findings were in conflict with that of Noorkoiv et al. [50] who showed that isometric force production only increased in knee angles closed to that adopted during training in short muscle length while no increment in force production was observed at all joint angles when training at long muscle length. Nevertheless, this study showed that hypertrophic changes were greater after training at long muscle length. One possible reason for the difference in findings between the studies could be due to the duration of the intervention. The duration of their study was 6 weeks while that of Kubo et al. [35] was 12 weeks. Noorkoiv et al. [50] stated that changes in force production after training at short muscle length was due to neural adaptation while any change in force production after training at long muscle length was due to increase muscle hypertrophy. Previous studies training using joint angle that induced long muscle length also involved more than 6 weeks of training [8, 16, 68]. More studies will be required to determine the optimal training duration when performing IST at long muscle length. In addition, although it has been shown that adopting a joint angle that induced longer muscle length resulted in strength adaptations across a larger range of movement, it is not known if there would be diminishing return if the muscle were to be stretch beyond a certain length. Furthermore, studies that compared the effects of IST at different muscle length have only investigated on the knee joint [3, 11, 35, 50, 51]. To our knowledge, no studies have compared the effects of IST at different muscle lengths for upper limbs.

Training at multiple joint angles

To our knowledge, there is only one study in the current literature that compared the effects of performing IST at single and multiple joint angles [56]. Participants in the study by Rasch and Pierson [56] had to either perform elbow flexion for 3 × 15 s at 90 ° elbow angle, or 1 × 15 s each at 60, 90 °, and 120 ° elbow angle, 5 times a week for 5 weeks. The result showed that significant increase in isometric forces at 3 different elbow angles in both groups (increment in single vs. multiple group – 60 °: 5.08 vs. 6.85 kg, 90 °: 5.62 vs. 5.85 kg, 120 °: 5.26 vs. 8.26 kg). There was no significant difference in changes in strength for all joint angles between the groups. Although this study has shown no significant difference in the change in isometric force at various joint angles between the 2 training methods, there was no comparison on the effects of single vs. multiple angles IST on dynamic performance. Results from separate studies suggested that performing IST at multiple joint angles resulted in superior dynamic and functional performance as compared to performing IST at single joint angle. For example, Folland et al. [19] showed that performing 4 × 10 × 2 s isometric leg extension at 4 angles and 75 % MVC resulted in superior gain in isometric strength and similar gain in isokinetic strength as performing isokinetic strength training. However, Knapik et al. [31] showed that performing 50 × 3 s isometric elbow extension at 90 ° elbow angle and 80 % MVC resulted in superior gain in isometric strength but inferior gain in isokinetic strength as compared to isokinetic strength training. Another study by Bimson et al. [10] found that participants improved their countermovement jump height after performing 3 s maximal leg extension at 7 knee angles, while Kubo et al. [36] found no improvement in participants who performed 10 × 15 s isometric leg press at 90° knee angle and 70 % MVC, even though the leg press would more likely fulfilled the training specificity principal for countermovement jump. Furthermore, the participants in the study by Bimson et al. [10] were amateur female soccer players, while those in Kubo et al. [36] were normal healthy adults, whose physical performance would have benefited more from any strength increment. These 2 comparisons suggest that performing IST at multiple joint angles would benefit dynamic and functional performance more than just performing IST at single joint angle.

Effects of isometric strength training on sports related dynamic performance

Jump performance

Jump performance has been shown to be a good indicator of performance for various sports [64]. Some studies have shown that IST improved concentric only jump [12, 36] but not countermovement and drop jump [4, 33, 37, 47], indicating that IST does not benefit movements that require the use of stretch shortening cycle (SSC) [33]. However, the studies by Bimson et al. [10], Bogdanis et al. [11] and Goldmann et al. [21] showed that performing IST led to improvement in countermovement and horizontal jump performances. In the study by Bogdanis et al. [11], participants were required to perform maximal isometric leg press at either 85° or 145° knee angles, with each repetition executed explosively and held for 3 s. Participants were also required to perform a total of 6 countermovement jumps during the rest intervals. The results showed that training at both knee angles led to 7.4–8.1 % improvement in countermovement jump height. This difference in findings from other studies could be due to 4 possible reasons. Firstly, most of the other studies have utilised single joint exercise during the IST while Bogdanis et al. [11] used a multijoint exercise. This could have been an effect of specificity in training. Secondly, IST was performed explosively in the study by Bogdanis et al. [11]. This method of training has been shown to be effective in improving explosive strength and RFD [5, 64], which is an important factor in jump performance [59]. Thirdly, Bogdanis et al. [11] included countermovement jumps during the rest interval. The addition of explosive dynamic exercise to IST could have enhanced the neuromuscular adaptations. Finally, another possible reason could be due to the joint angles adopted during IST. Although Bimson et al. [10] used a single joint exercise with slow build up to maximal isometric force, the participants in this study had to perform IST at 6 different knee angles (12°, 24°, 42°, 60°, 78°, 96° & 108°). This method of IST was also previously shown to benefit dynamic performance [19].

Running performance

Running is an endurance activity that requires repetitive muscle contractions. Determinants of performance for this activity include cardiovascular endurance, lactate threshold and movement economy [6]. Multiple studies have shown that participating in isotonic strength and/or plyometric training resulted in improved running performance without increase in maximal oxygen consumption [7, 41, 48, 53]. To our knowledge, there are currently only 2 studies that investigated the effects of IST on running performance [2, 18]. In the study by Albracht & Arampatzis [2], 13 long distance runners were recruited to performed 5 × 4 × 3 s isometric plantar flexion at MVC for 14 weeks. This isometric strength training intervention resulted in improved running economy reflected by decreased 5 and 3.4 % decrease in oxygen consumption, and 4.7 and 3.5 % reduction in energy cost, at running velocitites of 3 $m.s^{-1}$ and 3.5 $m.^{-1}$, respectively. These findings were supported by Fletcher et al. [18] that showed a 7 % improvement in running economy at 95 % of lactate threshold velocity in 6 highly trained male distance runners who performed 2 × 20 s isometric plantar flexion at 80 % maximum force, 3 times a week for 8 weeks. The magnitude of improvement in running economy in these 2 studies were higher than that observed in the study by Mikkola et al. [48] that showed young runners improving running economy at running speed of 14 km/h by 2.7 % after performing 8 weeks of plyometric and strength training; and that observed in the study by Beattie et al. [7] where competitive runners improved running economy by 3.5 % after 40 weeks of dynamic strength training. The improvement in running economy in the study by Albracht & Arampatzis [2] and Fletcher et al. [18] were accompanied by increased maximum plantar flexion force, muscle-tendon unit stiffness and elongation. The association of improved running economy and muscle-tendon unit stiffness were consistent with that of Paavolainen [53]. However, this association was in conflict with Kubo et al. [33] who suggested that increased stiffness post-IST would not be beneficial to activities involving SSC. It is possible that in order for IST to benefit activities that involves SSC, individuals will have to continue the activity in concurrent to performing IST. More studies on the effects of IST on running performance are required to confirm this statement.

Cycling performance

Cycling is also an endurance activity that has been shown to benefit from strength training [40, 62]. Loveless et al. [40] showed that 8 weeks of dynamic strength training alone improved peak power by 3.3 %. While Sunde et al. [62] showed that 8 weeks of dynamic strength training in concurrent with cycling training improves cycling economy by 4.8 % in competitive cyclists. Currently, the study by Zoladz et al. [73] is the only available study on the effects of IST on cycling performance. In this study, participants performed 2 × 5 × 5 s maximal isometric leg extensions 4 times a week for 7 weeks, without any cycling training. The results showed that there was improvement in power output at VO_{2peak} (3.9 %) and cycling economy below and above lactate threshold (3.7 % and 3.9 %, respectively). The improvement in power output at VO_{2peak} was comparable to that observed in the study by Loveless et al. [40]. This suggests that IST might provide similar benefit to cycling performance as dynamic mode of strength training. A correlational study by Stone et al. [59] showed that isometric peak force of the lower limb was correlated to Wingate peak power (r = 0.74 – 0.90) and track cycling split time (r = – 0.49– – 0.55). Correlation does not necessarily indicate causation. However, the findings of Zoladz et al. [73] showed that increasing isometric strength could in fact lead to improvement in cycling performance.

Soccer related skills performance

Soccer is a popular team sport that involves intermittent high intensity activities like sprinting, jumping and kicking of the ball. Stronger athletes have been shown to perform better at these activities [60]. Bimson et al. [10] investigated the effects of IST for the knee extensor on the performance of soccer related skills. The results showed improvement in countermovement jump height (2.24 %) and ball kicking distance (8.8 %), but no improvement to sprint and agility performance. The improvement in kicking performance was comparable with previous findings (11.5 %) that used dynamic and explosive mode of strength training for a longer intervention period (8–12 weeks) [23, 57]. Possible reasons for the lack of improvement in sprint and agility might be because of the training protocol in which maximal isometric contraction was developed over a 3 s period instead of explosively, and the lack of biomechanical specificity in training. Balshaw et al. [5] and Tillin and Folland [65] have shown that performing IST resulted in greater improvement in RFD, which is more applicable to sprinting and agility [60], than slow build-up protocol.

Other sports related skills performance

The benefits of IST also extended to Muay Thai strike and bouldering grip performances [38, 39]. Lee and McGill [38] compare the effects of IST and dynamic strength training for the core muscle on Muay Thai strikes performance and found that IST led to greater improvement in strike impact as compared to dynamic core muscle exercises. In a study on bouldering performance, Levernier and Laffaye [39] found that 4 weeks of IST for the fingers resulted in increased maximum force and RFD while gripping different crimps.

In summary, performing IST has been shown to have positive effect on different sports performance. However, the efficacy of IST on improving the performance of activities that involve SSC remains unclear. The continuous performance of these activities in concurrent with IST might be required in order to elicit improvement.

Currently, no studies have investigated the effects of IST on the performance of water sports such as swimming and kayaking. It is possible that IST might benefit the performance of these sports. Another sport that might benefit from IST is gymnastic, specifically the rings event. Some of the skills on the rings involved static hold or relatively slow movement [15]. One example of these skills is the still ring cross, which is characterised by maintain shoulder abduction at 90° with extended elbow held for at least 2 s while suspended on the rings. Gymnasts require a high level of muscular strength in the shoulder joint, which is commonly developed using various forms of training such as pulleys, elastic tubes or partner work [15]. As this skill involves mainly isometric contraction of the muscle, performing IST would be a form of specific strength training. In addition, there are limited numbers of studies comparing the effects of IST and dynamic strength training on sports related dynamic performance. These studies will provide coaches with knowledge to improve the training programs for their athletes.

Conclusion

Isometric strength training is a viable alternative mode of strength training that has been shown to induce less fatigue than dynamic strength training, result in superior angle specific strength than dynamic strength training, and benefit various sports related dynamic performances. Coaches and athletes may include IST into their training regime 1) to avoid getting overly fatigue while still acquiring positive neuromuscular adaptations, 2) to improve the strength at a biomechanically disadvantaged joint position of a specific movement, 3) to improve sports specific movement that require mainly isometric contraction such as performing the cross on gymnastic rings or rugby scrum, and 4) when athletes are having limited mobility due to injuries or post-surgery. It is recommended that IST be performed in concurrent with dynamic strength exercises as performing IST alone might not be beneficial to activities that involve the 3 phases of stretch shortening cycle such as CMJ. In addition, the effects of IST alone on strength trained athletes have not been well studied. When the objective of training is to increase muscle hypertrophy, IST should be performed at 70–75 % of MVC with sustained contraction of 3–30 s per repetition, and a total sustained contraction duration of > 80–150 s per session for > 36 sessions, while adopting a joint position that induces long muscle length. If the objective is to increase maximum strength, IST should be performed at 80–100 % MVC with a with sustained contraction of 1–5 s, and a total contraction time of 30–90 s per session, while adopting multiple joint angles or specifically targeted joint angle. It is also recommended that IST to be performed in a ballistic manner so as to maximise the improvement of RFD.

Conflict of Interest

Authors declare that they have no conflict of interest.

References

[1] Abernethy P, Wilson G, Logan P. Strength and power assessment – issues, controversies and challenges. Sports Med 1995; 19: 401–417

[2] Albracht K, Arampatzis A. Exercise–induced changes in tricep surae tendon stiffness and muscle strength affect running economy in humans. Eur J Appl Physiol 2013; 113: 1605–1615

[3] Alegre LM, Ferri-Morales A, Rodriguez-Casares R, Aguado X. Effect of isometric training on the knee extensor moment-angle relationship and vastus lateralis muscle architecture. Eur J Appl Physiol 2004; 114: 2437–2446

[4] Ball JR, Rich GQ, Wallis EL. Effects of isometric training on vertical jumping. Res Q 1964; 35: 231–235

[5] Balshaw T, Massey GJ, Maden-Wilkinson TM, Tillin NA, Folland JP. Training-specific functional, neural, and hypertrophic adaptations to explosive- vs. sustained-contraction strength training. J Appl Physiol (1985) 2016; 120: 1364–1373

[6] Bassett DR, Howley ET. Limiting factors for maximum oxygen uptake and determinants of endurance performance. Med Sci Sports Exerc 2000; 32: 70–84

[7] Beattie K, Carson BP, Lyons M, Rossiter A, Kenny IC. The effect of strength training on performance indicators in distance runners. J Strength Cond Res 2017; 31: 9–23

[8] Behm DG, Sale DG. Intended rather than actual movement velocity determines velocity-specific training response. J Appl Physiol (1985) 1993; 74: 359–368

[9] Beltman JGM, van der Vliet MR, Sargeant AJ, de Haan A. Metabolic cost of lengthening, isometric and shortening contractions in maximally stimulated rat skeletal muscle. Acta Physiol Scand 2004; 182: 179–187

[10] Bimson L, Langdown L, Fisher JP, Steele J. Six weeks of knee extensor isometric training improves soccer related skills in female soccer players. Journal of Trainology 2017; 6: 52–56

[11] Bogdanis GC, Selima E, Methenitis S, Veligekas P, Tsoukos A, Terzis G. Changes in muscle strength and vertical jump performance after short-term isometric training at different knee angles. Med Sci Sports Exerc 2014; 46: 252

[12] Burgess KE, Connick MJ, Graham-Smith P, Pearson SJ. Plyometric vs. isometric training influences on tendon properties and muscle output. J Strength Cond Res 2007; 21: 986–989

[13] Chui EF. Effects of isometric and dynamic weight-training exercises upon strength and speed of movement. Res Q 1964; 35: 246–257

[14] Davies J, Parker DF, Rutherford OM, Jones DA. Changes in strengh and cross sectional area of the elbow flexors as a result of isometric strength training. Eur J Appl Physiol 1988; 57: 667–670

[15] Dunlavy JK, Sands WA, McNeal JR, Stone MH, Smith SL, Jemni M, Haff GG. Strength assessment in a simulated men's still rings cross. J Sports Sci Med 2007; 6: 93–97

[16] Ebersole KT, Housh TJ, Johnson GO, Perry SR, Bull AJ, Cramer JT. Mechanomyographic and electromyographic responses to unilateral isometric training. J Strength Cond Res 2002; 16: 192–201

[17] Fisher NM, Pendergast DR, Gresham GE, Calkin E. Muscle rehabilitation: its effect on muscular and functional performance of patients with knee osteoarthritis. Arch Phys Med Rehabil 1991; 72: 367–374

[18] Fletcher JR, Esau SP, MacIntosh BR. The effect of isometric training on muscle tendon unit stiffness of medial gastrocnemius and the economy of locomotion in highly-trained distance runners. Med Sci Sports Exerc 2008; 40: S392

[19] Folland JP, Hawker K, Leach B, Little T, Jones DA. Strength training: Isometric training at a range of joint angles versus dynamic training. J Sports Sci 2005; 23: 817–824

[20] Garfinkel S, Cafarelli E. Relative changes in maximal force, EMG, and muscle cross-sectional area after isometric training. Med Sci Sports Exerc 1992; 24: 1220–1227

[21] Goldmann JP, Sanno M, Willwacher S, Heinrich K, Brüggemann GP. The potential of toe flexor muscles to enhance performance. J Sports Sci 2013; 31: 424–433

[22] Hagberg M, Harms-Ringdahl K, Nisel R, Hjelm EW. Rehabilitation of neck-shoulder in women inducstrial workers: a randomized trial comparing isometric shoulder endurance training with isometric shoulder strength training. Arch Phys Med Rehabil 2000; 81: 1051–1058

[23] Haldankar SR. Effect of strength training exercise on instep kick performance of soccer players. IJPEFS 2014; 3: 56–60

[24] Harris DJ, Atkinson G. International journal of sports medicine - ethical standards in sport and exercise science research. Int J Sports Med 2017; 38: 1126–1131

[25] Ikai M, Fukunaga T. A study on training effect on strength per unit corss-sectional area of muscle by means of ultrasonic measurement. Eur J Appl Physiol 1970; 28: 173–180

[26] Jones DA, Rutherford OM. Human muscle strength training: The effects of three different regimes and the nature of the resultant changes. J Physiol 1987; 391: 1–11

[27] Kanehisa H, Miyashita M. Effect of isometric and isokinetic muscle training on static strength and dynamic power. Eur J Appl Physiol 1983; 50: 365–371

[28] Kanehisa H, Nagareda H, Kawakami Y, Akima H, Masani K, Kouzaki M, Fukunaga T. Effects of equivolume isometric training programs comprising medium or high resistance on muscle size and strength. Eur J Appl Physiol 2002; 87: 112–119

[29] Khouw W, Herbert R. Optimisation of isometric training intensity. Aust J Physiother 1988; 44: 43–46

[30] Kitai TA, Sale DG. Specificty of joint angle in isometric training. Eur J Appl Physiol 1989; 58: 744–748

[31] Knapik JJ, Mawdsley RH, Ramos MU. Angular specificity, and test mode specificity of isometric and isokinetic strength training. J Orthop Sports Phys Ther 1983; 5: 58–65

[32] Kubo K, Ikebukuro T, Yaeshima K, Yata H, Tsunoda N, Kanehisa H. Effects of static and dynamic training on the stiffness and blood volume of tendon in vivo. J Appl Physiol (1985) 2009; 106: 412–417

[33] Kubo K, Ishigaki T, Ikebukuro T. Effects of plyometric and isometric training on muscle and tendon stiffness in vivo. Physiol Rep 2017; 5: 1–13

[34] Kubo K, Kanehisa H, Fukunaga T. Effects of different duration isometric contractions on tendon elasticity in human quadriceps muscles. J Physiol 2001; 536: 649–655

[35] Kubo K, Ohgo K, Takeshi R, Yoshinaga K, Tsunoda N, Kanehisa H, Fukunaga T. Effects of isometric training at different knee angles on the muscle-tendon complex in vivo. Scand J Med Sci Sports 2006; 16: 159–167

[36] Kubo K, Yata H, Kanehisa H, Fukunaga T. Effects of isometric squat training on the tendon stiffness and jump performance. Eur J Appl Physiol 2006; 96: 305–314

[37] Lee SEK, de Lira CAB, Nouailhetas VLA, Vancini RL, Andrade MS. Do isometric, isotonic and/or isokinetric strength trainings produce different strength outcomes? J Bodyw Mov Ther 2018; 22: 430–437

[38] Lee B, McGill S. The effort of core training on distal limb performance during ballistic strike manoeuvres. J Sports Sci 2017; 35: 1768–1780

[39] Levernier G, Guillaume L. Four weeks of finger grip training increases the rate of force development and the maximal force in elite and world-top ranking climbers. J Strength Cond Res 2017, doi:10.1519/JSC.0000000000002230

[40] Loveless DJ, Weber CL, Haseler LJ, Scheider DA. Maximal leg-strength training improves cycling economy in previously untrained men. Med Sci Sports Exerc 2005; 37: 1231–1236

[41] Lum D, Tan F, Pang J, Barbosa TM. Effects of intermittent sprint and plyometric training on endurance running performance. 2016, J Sport Health Sci, doi:10.1016/j.jshs.2016.08.005

[42] Marks R. The effect of isometric quadriceps strength training in mid-range for osteoarthritis of the knee. Arthrit Care Res 1993; 6: 52–56

[43] Maffiuletti NA, Aagaard P, Blazevich AJ, Folland J, Tillin N, Duchateau J. Rates of force development: physiological and methodlogical cosiderations. Eur J Appl Physiol 116: 1091–1116

[44] Maffiuletti NA, Martin A. Progressive versus rapid rate of contraction during 7 week of isometric resistance training. Med Sci Sports Exerc 2001; 33: 1220–1227

[45] McGuigan MR, Netwon MJ, Winchester JB, Nelson AG. Relationship between isometric and dynamic strength in recreationally trained men. J Strength Cond Res 2010; 24: 2570–2573

[46] McGuigan MR, Winchester JB, Erickson T. The importance of isometric maximum strength in college wrestlers. J Sports Sci Med 2006; 5: 108–113

[47] McKethan JK, Mayhew JL. Effects of isometrics, isotonics, and combined isometrics-isotonics on quadriceps strength and vertical jump. J Sports Med Phys Fitness 1974; 14: 224–229

[48] Mikkola JS, Rusko H, Nummela A, Pollari T, Hakkinen K. Concurrent endurance and explosive type strength training improves neuromuscular and anaerobic characteristics in young distance runners. Int J Sports Med 2007; 28: 602–611

[49] Newham DJ, Jones DA, Turner DL, McIntyre D. The metabolic costs of different types of contractile activity of the human adductor pollicis muscle. J Physiol 1995; 488: 815–819

[50] Noorkoiv M, Nosaka K, Blazevich AJ. Neuromuscular adaptations associated with knee joint angle-specific force change. Med Sci Sports Exerc 2014; 46: 1525–1537

[51] Noorkoiv M, Nosaka K, Blazevich AJ. Effects of isometric quadriceps strength training at different muscle lengths on dynamic torque production. J Sports Sci 2015; 33: 1952–1961

[52] Nuzzo JL, McBride JM, Cormie P, McCauley GO. Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength. J Strength Cond Res 2008; 22: 699–707

[53] Paavolainen L, Hakkinen K, Hamalainen I, Nummela A, Rusko H. Explosive-strength training improves 5-km running time by improving running economy and muscle power. J Appl Physiol (1985) 1999; 86: 1527–1533

[54] Pavone E, Moffat M. Isometric torque of the quadriceps femoris after concentric, eccentric and isometric training. Arch Phys Med Rehab 1985; 66: 168–170

[55] Pucci AR, Griffin L, Carafelli E. Maximal motor unit firing rates during isometric resistance training in men. Exp Physiol 2006; 91: 171–178

[56] Rasch PJ, Pierson WR. One position versus multiple positions in isometric exercise. Am J Phys Med Rehab 1964; 43: 10–12

[57] Rubley MD, Haase AC, Holocomb WR. The effect of plyometric training on power and kicking distance in female adolescent soccer players. J Strength Cond Res 2011; 25: 129–134

[58] Schott J, McCully K, Rutherford OM. The role of metabolites in strength training II. Short vs. long isometric contractions. Eur J Appl Physiol 1995; 71: 337–341

[59] Stone MH, Sands WA, Carlock J, Callan S, Dickie D, Daigle K, Cotton J, Smith SL, Hartman M. The importance of isometric maximum strength and peak rate of force development in sprint cycling. J Strength Cond Res 2004; 18: 878–884

[60] Suchomel TJ, Nimphius S, Stone MH. The importance of muscular strength in ahletic performance. Sports Med 2016; 46: 1419–1449

[61] Suchomel TJ, Nimphius S, Bellon CR, Stone MH. The importance of muscular strength: training considerations. Sports Med 2018; 48: 765–785

[62] Sunde A, Støren Ø, Bjerkaas M, Larsen MH, Hoff J, Helgrerud J. Maximal strength training improves cycling economy in competitive cyclist. J Strength Cond Res 2010; 24: 2157–2165

[63] Symons TB, Vandervoort AA, Rice CL, Overend TJ, Marsh GD. Effcts of maximal isometric and isokinetic resistance training on strength and functional mobility in older adults. J Gerontol A Biol Sci Med Sci 2005; 60: 777–781

[64] Tanaka H, Ikezo T, Umehara J, Nakamura M, Umegaki H. Influences of fasicle length during isometric training on improvement of muscle strength. J Strength Cond Res 2016; 30: 3249–3255

[65] Tillin NA, Folland JP. Maximal and explosive strength training elicit distinct neuromuscular adaptations, specific to the training stimulus. Eur J Appl Physiol 2014; 114: 365–374

[66] Tillin NA, Pain MTG, Folland JP. Short-term unilateral resistance training affects the agonist-antagonist but not the force-agonist activation relationship. Muscle Nerve 2011; 43: 375–384

[67] Tillin NA, Pain MTG, Folland JP. Short-term training for explosive strength causes neural and mechanical adaptations. Exp Physiol 2012; 97: 630–641

[68] Ullrich B, Kleinoder H, Bruggermann GP. Moment-angle relations after specific exercise. Int J Sports Med 2009; 30: 293–301

[69] Ullrich B, Kleinoder H, Bruggermann GP. Influence of length-restricted strength training on athlete's power-load curves of knee extensors and flexors. J Strength Cond Res 2010; 24: 668–678

[70] Weir JP, Housh TJ, Weir LL. Electromyographic evaluation of joint angle specificity and cross-training after isometric training. J Appl Physiol (1985) 1994; 77: 197–201

[71] Weir JP, Housh TJ, Weir LL, Johnson G. Effects of unilateral isometric strength training on joint angle specificity and cross-training. Eur J Appl Physiol 1995; 70: 337–343

[72] Young K, McDonagh MJN, Davies CTM. The effects of two forms of isometric training on the mecahnical properties of the triceps surae in man. Pflügers Arch 1985; 405: 384–388

[73] Zoladz JA, Szkutnik Z, Majerczak J, Grandys M, Duda K, Grassi B. Isometric strength training lowers the O_2 cost of cycling during moderate-intensity exercise. Eur J Appl Physiol 2012; 112: 4151–4161