The evolving high bar longswing in elite gymnasts of three age groups

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The evolving high bar longswing in elite gymnasts of three age groups

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ABSTRACT
Chronological age classifies elite male gymnasts into developmental performance classifications: senior (18+ years), junior (14–18 years) and development (8–14 years). Here, we examine the influence of age and experience on the biomechanics of the high bar longswing across classifications. Joint angular kinematics and kinetics were obtained from 30 gymnasts performing three sets each of eight consecutive longswings. Differences between groups and relations between age, experience and key biomechanical variables were correlated. Kinetic variables and range of motion of the hip and knee were highest for development gymnasts. In all age groups, a dominant shoulder kinetic contribution was found, although circle location of the peak joint kinetics occurred earliest for junior gymnasts. Hip work contributed more prominently in development gymnasts. Age and experience were positively correlated to an increase in peak shoulder moments and powers and negatively correlated to peak hip and knee moments. The findings reveal that age and experience combine to influence the functional phase, joint kinematics and relative joint kinetic contribution, particularly with the senior group demonstrating a shoulder dominant technique. Changes in musculoskeletal loading across the age groups suggest that factors such as relative strength and practice may have influenced this joint mode transition of the longswing.

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KEYWORDS
Gymnastics; longswing; age groups; experience; biomechanics

INTRODUCTION
In sports, the athlete-environment interaction is influenced by many individual factors such as biological maturation (Malina et al., 2015), muscular strength (Suchomel et al., 2016), training age (Blijlevens et al., 2020) and amount of deliberate practice (Ericsson et al., 1993). Despite individual differences, sports tend to categorise talented young athletes by chronological age to identify those with the capacity to perform in competitions and train within specific groups (Lloyd et al., 2014). Chronological age, practice and individual effects on skilled performance have been studied in sports by examining multiple age groups of athletes (reaching task: Streepey & Angulo-Kinzler, 2002; judo: Miarka et al., 2012; gymnastics; Busquets et al., 2013).

Whiteside et al. (2012) assessed age group tennis serve kinematics and found that younger players restrained upper limb movement, thereby reducing the functional degrees of freedom (DF) to ensure success (Bernstein, 1967; Vereijken et al., 1992). In contrast, cricket batting (Pinder et al., 2012) and freestyle swimming (Seifert et al., 2014) in junior performers have shown inherent movement degeneracy to adapt to changing demands, increasing the functional DF for success. It has been proposed that DF control is task-specific (Davids et al., 2008; Gray, 2020; Newell, 1986, 1996) and can vary between phases of the same movement, meaning coaches must recognise the task relevant control strategies to best fit their athletes. Understanding biomechanical similarities and differences across age groups can help to understand the place of DF control in age-related motor skill acquisition, set coaching expectations and offer more age-group-specific skill understanding of technique.

Early specialisation sports such as gymnastics give rise to many chronological age groups of athletes due to the younger age of entry (Myer et al., 2015). This specialisation often results in increased coach contact and training volume across 12 months of the year (Caine et al., 2013). Within early specialisation sports, it is often the case that chronological age, experience and practice accumulation increase together. A gymnast aged eight years old may have one year of gymnastics experience and an accumulation of over 440 h of scheduled coach-led practice across that single year. At 15 years old, experience would increase to eight years and over 4290 practice hours (practice hours estimated based on Baxter-Jones and Helms (1996) median values). By 20 years old, a gymnast may have up to 15 years of gymnastics experience, and over 7000 h of systematic practice. The interactive influences of chronological age and experience on gymnastic performance are not well understood.

Performance-level, male gymnasts in the UK compete in chronological age groups, starting at the development performance pathway (8–14 years), moving through to junior (14–18 years) and senior (18+ years) elite squads. Core skills such as the backflip on floor, double-leg circle on pommel horse and the high bar backwards longswing are performed by all gymnasts within the elite pathway, adhering to the same technical criteria (British Gymnastics, 2020). The high bar longswing (Figure 1) in particular is an essential skill that supports the development of more complex high bar skills (Irwin & Kerwin, 2007a; Readhead, 2011). The...
biomechanics of successful longswings for senior gymnasts are well understood, with joint kinematics, kinetics and coordination presented across many elite male cohorts (i.e., Arampatzis & Brüggemann, 2001; Hiley & Yeadon, 2016; Irwin & Kerwin, 2007b; Okamoto et al., 1987). Specifically, the hip and shoulder flexion and extension actions, labelled the “functional phases” (Irwin & Kerwin, 2005), have been identified as the key kinematics associated with longswing performance (Arampatzis & Brüggemann, 1999; Hiley & Yeadon, 2003). Other researchers have also explored features of the longswing such as joint energetics (Arampatzis & Brüggemann, 2001; Williams et al., 2015) and bar reaction forces (Irwin et al., 2021a, 2021b; Sheets & Hubbard, 2009) providing a comprehensive understanding of the senior elite longswing; however, less is known of the longswing biomechanics of younger elite gymnasts.

Busquets et al. (2013) analysed longswing kinematics across gymnast age groups, finding that older, more experienced gymnasts displayed later peak hip extension to begin the functional phase and later onset of peak hip flexion during the upswing phase. Similarly, Williams et al. (2015) and Irwin et al. (Irwin et al., 2021a, 2021b) found that as gymnasts learn the longswing, the functional-phase characteristics shift later in the circle, alongside a later maximum energy input. The later onset of these events promotes a more aesthetic, extended body position during earlier longswing phases, as well as ensuring sufficient energy input to maintain angular momentum (Irwin & Kerwin, 2007b; Irwin et al., 2019). However, both Williams et al. (2015) and Irwin et al. (2021a, 2021b) used novice adults to investigate skill learning and, therefore, may be less representative of youth gymnast skill progression. Within age group gymnasts, Vicinanza et al. (2018) and Burton et al. (2021) found decreased movement complexity and more stable, predictive longswing biomechanics for senior gymnasts compared to junior and development gymnasts. Understanding of the kinetics of the elite longswing for younger gymnasts is needed to fully understand the underlying mechanisms that drive the joint-level movements alongside biomechanical similarities and differences across the elite age groups that contribute to overall longswing success.

This study investigated the differences in joint-level longswing biomechanics between chronological age groups (development, junior and senior), prescribed by the formal UK system, for elite-level male gymnasts. Identifying differences in joint angular kinematics and kinetics of the longswing will help to assess the suitability of age-based gymnast groups and provide coaches with more age and experience-level skill understanding of potential age-related movement strategies.

Materials and methods

The data presented are from the same participant groups as detailed in Burton et al. (2021).

Participants

Ethical approval was obtained from the Cardiff Metropolitan University Ethics committee (approval number 16/4/01 R). Voluntary informed consent was gained from 30 elite level male artistic gymnasts for participation in the study. For gymnasts under the age of 18 years, informed consent was provided by a legal parent or guardian. Gymnasts were grouped by chronological age into three groups: senior, junior and development based on UK elite gymnastics pathway criteria. Ten senior (age: 20 ± 3 yrs, gymnastics experience: 13 ± 3 yrs, mass: 64.0 ± 6.5 kg, stature: 1.65 ± 0.07 m), ten junior (age: 15 ± 1 yrs, gymnastics experience: 7 ± 1 yrs, mass: 49.4 ± 7.6 kg, stature: 1.59 ± 0.08 m), and ten development-level gymnasts (age: 10 ± 1 yrs, gymnastics experience: 4 ± 2 yrs, mass: 33.2 ± 6.6 kg, stature: 1.27 ± 0.16 m) participated in the study.

Gymnasts completed three sets of eight sequential looped longswings on a competition standard high bar. The looped longswing was used as all participants were familiar with the skill and the secure hand position minimised fall and slip risk compared to the chalked bar longswing. Irwin and Kerwin (2007b) further support the use of the looped longswing as minimal “functional phase” technique differences exist between the looped and chalked bar longswing.

Data collection

An automated CODAmotion analysis system (Charnwood Dynamics Ltd, Leicester, UK) sampling at 100 Hz captured all kinematic data. Two Cx1scanners provided a field of view exceeding 2.5 m around the centre of the bar (Williams et al., 2012). Five x XM-400 and three x XM-200 markers were attached to three QMBD four-marker drive boxes and placed on the high bar and gymnast. Markers were placed on the right side of the gymnast on the mid forearm, lateral epicondyle of the elbow, estimated glenohumeral joint centre of rotation, greater trochanter, lateral femoral condyle, lateral malleolus,
fifth metatarsophalangeal joint, with an additional marker fixed to the underside of the centre of the bar.

**Data analysis**

R analysis coding software (http://www.r-project.org) was used to examine horizontal and vertical directional marker data from the CODA output. Density values were acquired from De Leva (1996) and centre of mass (CM) location of the gymnast was estimated using the principle of moments, based on the body segment inertia parameters. Kinematic data were filtered with a fourth-order low-pass Butterworth filter, and Winter’s (2009) residual analysis was employed to establish the 12 Hz cut-off frequency. Circle angle ($\theta_{CA}$), distinguished by the CM to bar vector with respect to the horizontal, was used to define angular orientation of the gymnast around the bar. The position of CM directly above the bar (gymnast in handstand) was defined as 0° and 360° $\theta_{CA}$.

Similar to Whiteside et al. (2012) and Busquets et al. (2013), sagittal plane shoulder, hip and knee flexion-extension angle and angular velocities were calculated. Angular movement at the shoulder was obtained from the angle formed by the vectors joining elbow, shoulder, and greater trochanter markers, movements at the hip from the angle formed by the vectors joining the shoulder, greater trochanter and femoral condyle markers and knee movement from the angle formed by the greater trochanter, femoral condyle, and lateral malleolus markers. Flexion of the hip joint and extension of the shoulder and knee joint was defined as positive. Zero degrees of the shoulder, hip and knee angle was determined as the gymnast was in handstand above the bar. The longswing was split into three phases: downswing, kinematic functional phase (FPk) and upswing. The downswing was defined from 0° $\theta_{CA}$ to the onset of the FPk. The FPk was defined from the peak hyperflexion of the shoulders and hyper extension of the hips, to peak extension of the shoulder and flexion of the hips as gymnasts passed the lower vertical (Irwin & Kerwin, 2005). The upswing phase was determined from the end of the FPk to 359° $\theta_{CA}$.

Net joint moments were estimated for the shoulder, hip and knee using a two-dimensional inverse dynamics analysis (Winter, 2009). Kinematic and inertia data were combined with known zero forces at the toes. Gymnasts were modelled as a hinge-jointed system consisting of four segments (arm, trunk, thigh and shank) assumed to be rigid with a uniform density to allow for the estimation of net joint moments (Irwin & Kerwin, 2007b; Williams et al., 2015). Joint opening caused by net joint angular velocity and moment in the same direction was denoted as a positive action whilst joint opening with net joint angular velocity and moment in the opposite direction was labelled as a negative action. Estimations of shoulder and hip joint resultant power were calculated as the product of joint angular velocity and joint moment. Net joint mechanical work was determined from the integral of joint power with respect to time. Non-dimensional normalisation was used on joint moment, power and work data using an adapted version of Hof’s (1996) procedure. Joint moments (JM), power (JP) and work (JW) values of the $j$th joint were normalised using body mass ($m$), acceleration due to gravity ($g$) and height ($h$) of the participant ($p$). Equations 1, 2 and 3 define normalised JM (NJM), JP (NJP) and JW (NJW), respectively:

\[ NJM_j = JM_j / m_p g h_p \]
\[ NJP_j = JP_j / m_p g^{3/2} h_p^{1/2} \]
\[ NJW_j = JW_j / m_p g h_p \]

To allow for intra-trial comparisons, time-series data were interpolated to 1° increments of overall $\theta_{CA}$ about the bar.

**Statistical analysis**

A one-way analysis of variance (ANOVA) examined the differences between groups across all variables ($\alpha = 0.05$), followed by a Bonferroni post hoc test to determine where differences were found. A Bonferroni post hoc test was then used to examine where differences were found. Hedges g calculations were then used to generate between-group effect sizes ($g$) where small effect $= 0.2$, medium effect $= 0.5$ and large effect $= 0.8$ (Cohen, 1977). One-dimensional statistical parametric mapping (SPM) (spm1d, version M0.4.8, www.spm1d.org) provided statistical inferences across continuous variables of interest. Pairwise correlations were conducted between the age and experience of the whole gymnast cohort, against basic anthropometric measurements and peak joint kinetic and kinematic characteristics. Correlations were evaluated in line with Cohen’s (1988) guidelines: small ($r \pm 0.10$), medium ($r \pm 0.30$) and large ($r \pm 0.50$) in magnitude. Significance ($\alpha = 0.05$) of correlation coefficients was calculated from t-statistics. All statistical tests were completed in Matlab (The MathWorks Inc., USA, version R2022b).

**Results**

**Joint kinematics**

Development gymnasts showed significantly reduced shoulder extension at the end of the shoulder FPk ($p < 0.001$, $g = -1.26$; $-1.55$) and increased hip flexion at the end of the hip FPk ($p < 0.001$, $g = 0.15$; $0.34$) compared to senior and junior gymnasts.

<table>
<thead>
<tr>
<th>Table 1. Group mean (SD) shoulder ($\theta_s$) and hip ($\theta_h$) joint angles and circle angle ($\theta_{CA}$) positions for the start and end of the kinematic functional phase for senior, junior and development gymnasts.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group</td>
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</tr>
<tr>
<td>Senior</td>
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<tr>
<td>Junior</td>
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<tr>
<td>Dev</td>
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</table>

* significantly different to senior group ($p < 0.001$). ^ significantly different to junior group ($p < 0.001$). ** significantly different to development group ($p < 0.001$).
Junior gymnasts demonstrated a significantly earlier start position for the shoulder FPs compared to senior (p < 0.001, g = 0.61) and development groups (p < 0.001, g = 0.66) and significantly reduced hip extension at the start of the hip FPs compared to senior gymnasts (p < 0.001, g = −0.39).

All SPM ANOVA joint kinematic results displayed differences between groups (p < 0.05). All gymnast groups showed significantly different magnitudes of shoulder extension throughout the upswing phase (Figure 2, p < 0.001). At the hip joint, development gymnasts showed significantly greater flexion from 0°_CA to 130°_CA and 200°_CA to 359°_CA compared to senior and junior gymnasts (p < 0.001). The development group displayed significantly increased knee flexion across the whole swing compared to junior gymnasts (p < 0.001) and between 0°_CA and 355°_CA compared to senior gymnasts (p < 0.001).

**Joint moments**

Shoulder, hip and knee joint moment profiles showed significant differences between groups across the longswing (p <
Between 90°\textsubscript{CA} and 150°\textsubscript{CA} senior gymnasts showed increased shoulder extensor moments compared to junior gymnasts (p < 0.001). Development gymnasts demonstrated significantly different shoulder moments from 0°\textsubscript{CA} to 210°\textsubscript{CA} compared to senior gymnasts (p < 0.001). Development gymnasts showed significantly higher extensor moments from 0°\textsubscript{CA} to 180°\textsubscript{CA} and higher flexor moments from 270°\textsubscript{CA} to 360°\textsubscript{CA} compared to both senior (p < 0.001) and junior gymnasts (p < 0.001). Development gymnasts displayed significantly different knee joint moments for >95% of the long-swing compared to senior gymnast (p < 0.001), and junior gymnasts (p < 0.001).

**Joint powers**

Development gymnasts showed significantly higher shoulder joint power than junior gymnasts between 90°\textsubscript{CA} and 160°\textsubscript{CA} (Figure 4, p < 0.001), and senior gymnasts between 130°\textsubscript{CA} and

Figure 3. Group shoulder hip and knee joint moment profiles for senior, junior and development gymnasts. 1\textsuperscript{st} row: mean and standard deviation joint moment profiles. Bonferroni post hoc statistical parametric mapping: 2\textsuperscript{nd} row: junior-senior groups, 3\textsuperscript{rd} row: development-junior groups and 4\textsuperscript{th} row: development-senior groups joint moments.
150°CA (p < 0.001). However, development gymnasts showed lower shoulder power between 270°CA and 295°CA and from 320°CA to 360°CA compared to junior (p < 0.001) and senior gymnasts (p < 0.004). According to the hip joint power profiles (Figure 4), senior gymnasts exhibited significantly lower power than both junior and development gymnasts between 0°CA and 35°CA (p < 0.001). Knee joint power profiles differed between gymnast groups throughout the downswing and functional phases of the longswing (p ≤ 0.016).

**Joint work**

Junior gymnasts showed significantly lower shoulder joint work percentages during the downswing than senior (p < 0.013, g = 0.63) and development groups (p < 0.001, g = 1.20), with development gymnasts showing lower hip work percentages compared to juniors (p < 0.001, g = 1.11, Table 2). Within the upswing phase, differences were only found between knee joint work contributions for senior and junior gymnasts (p < 0.003, g = 1.10).

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**Figure 4.** Group shoulder hip and knee joint power profiles for senior, junior and development gymnasts. 1st row: mean and standard deviation joint power profiles. Bonferroni post hoc statistical parametric mapping: 2nd row: junior-senior groups, 3rd row: development-junior groups and 4th row: development-senior groups joint powers.
Within group variability (SD) was evident across all phases, all joints and all gymnast groups (Table 2).

Large positive correlations were found between chronological age, gymnast experience, total body mass and standing height (Table 3). As age and experience increased, medium to high increases in peak shoulder NJM and NJP were evident ($r = 0.35–0.54$, $p < 0.029$). However, peak hip flexion at FP<sub>k</sub> end, hip and knee NJM, knee NJM $\theta_{CA}$ position and knee NJP $\theta_{CA}$ position showed medium to large negative correlations with age and experience ($r = -0.48 - -0.65$, $p \leq 0.037$).

**Discussion**

This study examined the influence of age and gymnastics experience on the biomechanics of the high bar longswing across age group classifications. Although differences between age groups were shown for the functional phase and peak joint kinetic characteristics of the longswing, senior gymnasts did not demonstrate later onset of these events in the circle in accordance with previous studies of learning effects in the longswing (Busquets et al., 2013; Irwin et al., 2021a, 2021b) and Williams et al (2015, 2015). However, increasing chronological age and experience showed significant positive correlations for peak shoulder joint moments and powers, with peak hip and knee joint moments showing significant negative correlations.

**Joint kinematics**

Timing of the shoulder and hip joint actions is important for successful longswing performance (Busquets et al., 2013; Hiley & Yeadon, 2016). With multiple swing repetitions, it seems logical that gymnasts aim to use the same technique for each circle of the bar (Hiley et al., 2013; Wilson et al., 2008). All three of the gymnast groups showed an open shoulder angle during the downswing (Figure 2) to ensure a longer radius of rotation of the CM (George, 1980), before closing the shoulder angle to increase angular velocity in the upswing to reach handstand (Kopp & Reid, 1980). Similar to Hiley et al. (2013), all elite gymnast groups within our study demonstrated reduced joint variability (SD) during the shoulder and hip FP<sub>k</sub> (Figure 2). This variability can be seen as functional to performance, increasing consistency; vital to longswing success due to the mechanical link between the FP<sub>k</sub> positions and task outcome (Williams et al., 2012). Unlike Busquets et al. (2013), a later positioning of the hip FP<sub>k</sub> did not discriminate between age groups. Although within this research, all gymnasts were able to complete the full 360-degree longswing rotation, unlike some participants within Busquets et al. (2013) groups, which may have contributed to the differences mentioned.

The upswing phase of the longswing demonstrated most shoulder joint angle variation between groups (Figure 2). These findings support the observations of Hiley et al. (2013) that in the less mechanically important upswing phase, increased feedback control may be used to deal with swing changes. Increased joint variability within the upswing can be associated, through the process of releasing DF (Bernstein, 1967), with expert performance, where more variable movement plays a functional role in stabilising other aspects or increasing movement outcome consistency (Hamill et al., 1999; Van Emmerik et al., 2005). Although effective shoulder movement can be the most difficult to attain when learning the longswing (Williams et al., 2012), these similarities across age groups are not surprising due to the basic nature of the longswing skill.

All gymnasts in this research study were able to successfully complete the longswing. Although according to Bernstein (1967), the development gymnasts, the group to most recently achieve skill success, may still be searching for the most efficient solutions to the movement problem. Development gymnasts showed increased hip flexion in the downswing and

<table>
<thead>
<tr>
<th>Table 2. Group mean average (SD) shoulder, hip and knee percentage joint work contributions for the three longswing phases (downswing, functional phase and upswing) for senior, junior and development gymnasts.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downswing Joint Work %</td>
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<td>Group</td>
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<tr>
<td>Senior</td>
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<td>Junior</td>
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<td>Dev</td>
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* significantly different to senior group ($p < 0.001$). $^*$ significantly different to junior group ($p < 0.001$). $^*$ significantly different to development group ($p < 0.001$).

| Table 3. Correlation matrix for chronological age and experience against basic participant characteristics, joint kinematic and joint kinetic characteristics for elite male gymnasts ($n = 30$). |
|-------------------|-------------------|-------------------|
| Anthropometrics | | |
| Experience | 0.90* | 0.84* | 0.82* |
| Total body mass | 0.80* | 0.77* |
| Standing height | | |
| Kinematic Functional Phase (FP<sub>k</sub>) | | |
| $\theta_1$ @ FP<sub>k</sub> start ($^\circ$) | 0.14 | 0.29 |
| $\theta_1$ @ FP<sub>k</sub> position @ FP<sub>k</sub> start ($^\circ$) | 0.03 | 0.05 |
| $\theta_1$ @ FP<sub>k</sub> end ($^\circ$) | 0.07 | 0.01 |
| $\theta_1$ @ FP<sub>k</sub> position @ FP<sub>k</sub> end ($^\circ$) | 0.01 | 0.17 |
| $\theta_1$ @ FP<sub>k</sub> start ($^\circ$) | 0.23 | 0.27 |
| $\theta_1$ @ FP<sub>k</sub> position @ FP<sub>k</sub> end ($^\circ$) | 0.04 | 0.06 |
| $\theta_1$ @ FP<sub>k</sub> end ($^\circ$) | -0.63* | -0.48* |
| $\theta_1$ @ FP<sub>k</sub> position @ FP<sub>k</sub> end ($^\circ$) | 0.02 | 0.20 |
| Relative Peak Joint Moment | | |
| Shoulder joint normalised joint moment (NJM) | 0.35* | 0.36* |
| Hip joint normalised joint moment (NJM) | -0.20 | -0.17 |
| Hip joint normalised joint moment (NJM) | -0.65* | -0.45* |
| Knee joint normalised joint moment (NJM) | -0.55* | -0.55* |
| Knee joint normalised joint position (NJM) | -0.52* | -0.33* |
| Relative Peak Joint Power | | |
| Shoulder joint normalised joint power (NJP) | 0.54* | 0.43* |
| Hip joint normalised joint power (NJP) | -0.21 | -0.09 |
| Hip joint normalised joint power (NJP) | -0.20 | -0.06 |
| Knee joint normalised joint power (NJP) | -0.19 | -0.24 |
| Knee joint normalised joint position (NJP) | -0.60* | -0.56* |

Notes: $\theta_1$, shoulder joint angle; $\theta_1$, hip joint angle; $\theta_{CA}$, circle angle; FP<sub>k</sub>, kinematic functional phase; coefficient (r) based on Cohen (1988); * significant relationships between variables ($\alpha = 0.05$).
upswing phases, the largest hip angle range of motion and knee flexion throughout the swing compared to senior and junior groups (Table 1, Figure 2). The increased hip and knee joint movement could be a result of the gradual releasing of the DF, particularly in the downswing and upswing, where adaptability may be required to ensure precision of the FP, (Hiley & Yeadon, 2016). Development gymnasts may still be exploring the hip and knee joint positions for success, not yet adhering to the full knee extension required for adherence to the Code of Points (Federation Internationale de Gymnastique FIG, 2021).

**Joint kinetics**

Williams et al. (2015) found that successful novice longswing technique showed three specific power inputs at the hip: the first attributed to joint hyperextension near the lower vertical, the second for flexion during the FP, and the third required to reach handstand. However, within this research, hip power profiles more closely resembled those shown by Irwin and Kerwin (2007b) for more skilled gymnasts, whereby the final hip power profile peak was not required to reach handstand. This reduced hip power requirement was shown for all elite gymnast groups, despite the lower level of experience for development gymnasts (Figure 4). As mentioned previously, this could be due to the simplicity of the longswing skill for elite gymnasts, and the likely early skill mastery in their careers.

Trends congruent with previous research for elite gymnasts were also evident for joint work contributions. All gymnast groups showed shoulder work dominance compared to the hip during all longswing phases (Table 2). Okamoto et al. (1987) and Irwin and Kerwin (2007b) found that the shoulder joint was responsible for 48% and 55%, respectively, of the total joint work in the longswing. Our study found similar results, showing a shoulder work dominance of ≥54% for all groups across the longswing, supporting the notion that effective use of the shoulder joint is a key feature of skill success (Arampatzis & Brüggemann, 1999; Hiley et al., 2013), despite differences in chronological age and experience.

Across all age groups, the peak joint kinetics occurred within the FP, emphasising the importance of these phases to longswing success (Irwin & Kerwin, 2007b). However, differing positions of the peak shoulder and hip joint moment and power inputs within the FP, across age groups was evident (Figures 3 and 4). The varied positions of the peak kinetics refer offering reasoning for the increased joint kinematic variability within the other longswing phases, to ensure the full rotation could still be completed (Hiley & Yeadon, 2016). Development gymnasts displayed both higher and later knee joint moments and hip joint moments and powers compared to senior and junior groups (Figures 3 and 4) potentially explaining the significantly higher hip flexion shown by development gymnasts at the end of the FP, (Table 1). The increased hip joint moment and power towards the later stage of the FP, may be a necessary compensatory mechanism for the lower shoulder joint power input in the FP, for development gymnasts.

**Age and experience correlations**

Significant positive correlations observed between chronological age, experience and shoulder kinetics (Table 3), concurred with the findings from previous research in elite (Irwin & Kerwin, 2007b; Okamoto et al., 1987), experienced (Tsuchiya et al., 2004) and novice gymnasts (Williams et al., 2015). Specifically, the older and more experienced gymnasts displayed a more dominant shoulder joint contribution to successful longswing technique compared to the hip joint. The reduced hip kinetics resulted in a reduced joint range of motion (Table 1), promoting a more aesthetic, stretched body position during the longswing, more closely replicating the technique outlined in the Code of Points (Federation Internationale de Gymnastique FIG, 2021). The significant relationships found in this study highlight the reorganisation of the joint kinetic contributions to the longswing, reflecting findings from Williams et al. (2015) and Irwin et al (2021a, 2021b), who examined the longswing across a learning period in novice gymnasts.

Throughout development, factors such as muscular strength and biological maturation are known to undergo nonlinear changes (Grimm et al., 2011) and may contribute to movement pattern emergence (Haywood & Getchell, 2020). In future, quantifying gymnast’s physical capabilities and maturational factors, alongside a more independent manipulation of chronological age and experience, could help to reveal additional contributing elements to changes in longswing biomechanics across groups. Equally, differing coaching environments and instruction can contribute to longswing performance differences. Future research should track longitudinally as gymnasts progress through the age groups. The sole recruitment of gymnasts affiliated with the same governing body and UK elite pathway was an attempt to regulate this.

One limitation of the study is that the constructs of age and experience are confounded, which is a typical feature of elite gymnasts who are experienced and skilled. The shift in the coordination mode (functional-phase location and joint kinematics) combined with and the transition to a more shoulder dominant action leads to the suggestion that some key considerations for the development of this skill include relative strength and practice volume. These joint mode transitions are most likely task dependent and influenced by the biological maturation of the gymnast. In addition, it should be noted that the application of De Leva’s (1996) data was extended not only to senior gymnasts (18–26 years old), but to junior (14–17 years old) and development gymnasts (9–13 years old). More age-specific segment data could be applied to the different groups in future. The kinematic model used in this study replicates those successfully used by Hiley and Yeadon (2003), Irwin and Kerwin (2007b), Williams et al. (2012), however, the motion of the torso is not considered. Therefore, future research should consider separating the trunk into smaller segments, due to the role the trunk may play (Readhead, 2011).

Although the Code of Points (FIG, 2021) dictates a large portion of the joint kinematics and the movement outcome, elite gymnasts across chronological age groups display multiple individual solutions within these rules that can be used to perform successfully. All groups displayed shoulder work dominance compared to the hip and knee joint, reinforcing the findings of Okamoto et al. (1987), Irwin and Kerwin (2007b) and Williams et al. (2015) that adequate shoulder joint work is a determining factor of the elite longswing. Differences were evident between and within gymnast
groups, suggesting that care needs to be taken when generalising senior gymnast biomechanics to other age categories of gymnasts. The notion of a gold standard model of performance from a senior gymnast may not be most appropriate for a younger gymnast to be successful performing the longswing.

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Disclosure statement

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