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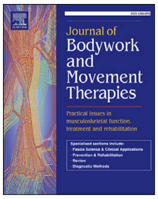

Prevention and Rehabilitation

Can lower extremity anatomical measures and core stability predict dynamic knee valgus in young men?

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ABSTRACT

Introduction: Dynamic knee valgus (DKV) is a risk factor for lower extremity injuries such as anterior cruciate ligament and patellofemoral pain syndrome. Purpose of the current study was to investigate the relationship between lower extremity anatomical measures (LEAM) and core stability with DKV during the single-leg squat.

Methods: Thirty healthy men aged between 18 and 28 years participated in this cross-sectional biomechanical study.DKV was assessed using a 6-camera motion analysis system during a single-leg squat task. Anteversion of hip, hip internal and external rotation, Q-angle, knee hyperextension, tibial torsion, tibia vara, plantar arch index, and core stability were measured using standard clinical procedures. To predict DKV, a multiple linear regression model was used.

Result: The stability index negatively and plantar arch index positively predicted greater DKV during the single-leg squat task ($P = 0.001$ and $P = 0.09$, respectively). Research variables together predicted 82% of the variance in DKV ($F(4,26) = 28.09$, $p < 0.001$). However, relationships between other variables and DKV were not found.

Conclusion: The core stability index and plantar arch index were associated with observed DKV during the single-leg squat. These results suggested that proximal and distal variables to the knee should be considered when evaluating individuals who present DKV during the single-leg squat.

1. Introduction

Excessive dynamic knee valgus (DKV) is believed to be a significant contributor for non-contact knee injuries (Bell et al., 2013; Schmitz et al., 2009). It places stress on passive tissues (Claiborne et al., 2006) and develops overuse injuries like patellofemoral pain syndrome and acute injuries such as anterior cruciate ligament (Holden et al., 2017; Sigward et al., 2011). Excessive frontal and transverse plane knee movements, especially knee valgus and hip internal rotation, increase stress on the patellofemoral complex; therefore it enhances the risk of patellofemoral pain syndrome (Lee et al., 2014). DKV is a common faulty movement pattern in the lower extremity, which is a combination of femoral and tibial motions(Claiborne et al., 2006; Holden et al., 2017; Lee et al., 2014; Sigward et al., 2011). The DKV can be affected by the proximal and distal segments to the knee joint, including the trunk, hip, leg, and foot (Bell et al., 2013). Given the relationship between DKV and knee loading, screening subjects characteristics throughout dynamic tasks such as single-leg squat have been promoted as a way to recognize those at risk of knee injury (Sigward et al., 2008). Therefore, the identification of predictive factors of DKV is necessary to reduce the risk of subsequent sequelae.

The comprehensive approach suggests a model of risk factor categories (neuromuscular and biomechanical)(Chuter et al., 2012) for identifying the potential risk factors that may develop the "at-risk" knee dynamic positions such as DKV (Nguyen et al., 2011). Among others, neuromuscular control of the hip musculature is one of the essential factors in affording proximal stability for distal segment motion (Chuter and de Jonge 2012). Previous studies declared alteration in hip muscle function can lead to the poor

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lower extremity kinematics such as DKV (Dix et al., 2019; Stickler et al., 2015; Ugalde et al., 2015).

Lower extremity anatomical measures (LEAM) can be one of the most important contributing factors for increased DKV during dynamic task such as single-leg squat (Nguyen et al., 2011). Changes in LEAM may create compensatory changes in alignment in other related segments, which may result in deviated stress patterns on involved segments (Sung et al., 2017). So through the changes in LEAM can be most important in increased DKV because it can be underlying causes of above mentioned neuromuscular dysfunction in the lower extremity. This premise can be proven by studies suggesting any changes in hip muscle characteristics such as length, tension, or orientation affect on the muscle moment arms, directly, which influence hip muscle functions (Cibulka et al., 2010; Nguyen et al., 2011; Powers 2010). Thus changes in LEAM may result to changes in the force and activation production characteristics of the hip muscle. For example, coupling mechanism states foot pronation leads to internal tibial rotation and femoral internal rotation causing a position which is proposed to creating a valgus position, and this conditions changed pelvis position, that is suggested this change can increased strain on hip and pelvis muscles (Dix et al., 2019). Although it is assumed that change in LEAM potentially by altering the length, tension, and orientation characteristics of the muscles and their final torque-producing cabilities can contribute to creating DKV, whether each of single parameters of LEAM that can contribute in DKV predicting is unclear. Moreover, investigations in previous studies were limited to only one factor of LEAM or select LEAM characteristics (Rath et al., 2016; Uota et al., 2017), and no studies have addressed the relationship between a collective set of LEAM variables that describe lower extremity posture sufficiently.

Moreover, the reported results were conflicting, for instance, Bittencourt et al. (2012) stated a positive relationship among DKV and passive internal rotation of hip (Bittencourt et al., 2012), while Bell et al. (2008) stated a positive association between DKV and external rotation of hip (Claiborne et al., 2006) or Kothori et al. (2016) concluded that low arch foot index could be related with increased DKV (Kothari et al., 2016) while Rath et al. (2016) did not report any relationship among foot type and DKV (Rath et al., 2016).

On the other hand, each specific joint dynamic stability, such as knee joint, depends on neuromuscular control of every proximal and distal involved segments, including trunk control throughout the dynamic movement (J. M. Burnham et al., 2016). The term of core stability, in sports medicine literature, referred to a foundation for dynamic control of the trunk that permits force production, control and transferring, and also control of the motion in distal segments of the lower extremity kinetic chain (De Blaiser et al., 2018). Hodges and Richardson (Hodges et al., 1997) reported that trunk muscle activation often happens before the activity of the lower extremity muscles. Any deficiency in neuromuscular control of the core muscle performance may cause uncontrolled trunk displacement thorough functional activity, that can place the lower extremity in a valgus position and enhance the risk of knee injuries (Jamison et al., 2013; Raschner et al., 2012). Poor neuromuscular control of core muscles may also compromise the lower extremity dynamic stability and results in enhanced abduction torque at the knee and lead to at-risk positions such as DKV (B. T. Zazulak et al., 2007). These results draws more attention to the importance of the core muscle performance for both prevention and rehabilitation of the knee injuries (Fredericson et al., 2005). Nevertheless, the number of studies paying attention to the importance of core muscle rule in lower extremity motion is infrequent, and the results are also unclear. For instance, Burnham et al. (2016a,b) and Shirey et al. (2012) showed that core stability had a positive effect on DKV (Jeremy M Burnham et al., 2016; Shirey et al., 2012). In contrast, Nakagawa et al. (2018) and Akins et al. (2013) did not find any association between core stability index's and DKV (Akins et al., 2013; Nakagawa et al., 2018).

Understanding the underlying variables that predict frontal and transverse plane knee motions such as DKV during dynamic tasks might help to identify at risk subjects for acute or chronic knee injuries and facilitate the development of prevention programs for knee injuries. Therefore, the aim of this study was to determine whether hip anteversion, hip internal and external rotation, Q angle, tibia torsion, knee hyperextension, tibia vara, plantar arch index variables and core stability index can predict DKV during single-leg squat task. It was assumed that the regression models of combined elements associated with LEAM and core stability would predict DKV with high sensitivity and moderate particularity.

2. Methods

2.1. Study design

This is a cross-sectional study conducted in the Biomechanics Research Laboratory. Ethical approval obtained from the University of Tehran ethics committee (ethic codes: RI.UT.REC.1395024). The protocol has been approved in the Iranian Registry of Clinical Trials at (IRCT20180821040843N1). The reporting of current study follows the guideline of 'Strengthening the Reporting of Observational Studies in Epidemiology' (STROBE) (Vandenbroucke et al., 2009).

2.2. Participants

Thirty healthy men aged 18 to 28 participated in cuurent study. All of the participants gave their informed consent. The average and standard deviation of age, height, and mass of the participants were 24.5 ± 2.5 years, 178.9 ± 7.2 cm, and 76.7 ± 2.5 kg, respectively. Exclusion criteria from the study were: the history of injury in any lower extremity segment that makes movement restriction (del Pozo-Cruz et al., 2013; Orishimo et al., 2010), the existence of any visible musculoskeletal deformities in the lower and upper extremity in normal standing posture (Farr et al., 2014; Lin et al., 2010), abnormal BMI, BMI<18 or BMI>28 (Di Angelantonio et al., 2016).

2.3. Procedures

Clinical measures of the trunk and the lower extremity of the dominant leg (the leg kicking the ball) were obtained by the same examiner as follow:

2.4. Reliability of measures

Before data collection, acceptable reliability for all clinical measures and DKV was established. To determine the intra-tester reliability for LEAM, measurements data of 10 subjects were obtained on two separate days with a one-week interval. Intra-class correlation coefficients for test-retest reliability (ICC3,1) were found to be substantial for all measures. Test-retest reliability was excellent (0.84<ICC<0.98) for all variables. Measures of DKV during the single-leg squat were acquired on five subjects on two separate days with a one week interval.

Anteversion of Hip: Graigs Test was used to evaluate the anteversion of the hip. The subject was asked to lie prone and flex the knee to 90° flexion. Then the examiner finds the posterior part of the greater trochanter by palpation and rotated the hip of the subject passively until the greater trochanter became parallel with the examination table. The angle between the vertical line and shaft of the tibia was recorded as the extent of the anteversion of the hip for each subject (Amraee et al., 2013; Choi et al., 2015).

Hip Internal and External Rotation (Hip IR/ER): Hip IR/ER was measured while the subject was sitting on the table so that his knee and hip were in 90° flexion. Then the subject was instructed to perform hip IR/ER rotation toward of the end of range of motion. Also, in this position, the movable arm of goniometer was placed on the tibia and its fixed arm on the ground perpendicularly. The fixed angle was recorded as hip IR/ER (Amraee et al., 2013).

Q Angle: To measure the Q angle, the centre of the goniometer was aligned with the centre of the patella. The Q angle was the angle between a line drawn from the anterior superior iliac spine (ASIS) to the centre of patella and an another line from the centre of patella to the tibial tuberosity (Weiss et al., 2013).

Knee Hyperextension: The subject was asked to keep a normal standing position. Then the centre of the goniometer was placed on the femoral epicondyle, and its arms were placed parallel to the hip greater trochanter and the central line of the tibia lateral section. The fixed angle was recorded as knee hyperextension (Amraee et al., 2013; Loudon 2000).

Tibial Torsion: To measure the tibial tortion Tight-foot method was used in this study. The subject was asked to lie in prone position on the table with the knee joint flexed in 90°, the centre of the heel was marked in the plantar surface of the foot. The angle created between a line drawn from the centre of the heel to the middle of the foot and a line dividing the hip into two halves was recorded as a tibial torsion angle (Amraee et al., 2013).

Tibia Vara: in order to measure tibia vara in this study, the subject was asked to stand on a single leg, keep the toes of the opposite foot in contact with the floor to keep balance, and look at a point in their front. Then, the examiner stood behind the subject, drew a line dividing the posterior part of the calf into two halves, and a line from upper 2/3 of the calf to the top of the ankle. The angle formed between this line and the floor was recorded as tibia vara (Amraee et al., 2013).

Arch Index: The Staheli index was used to measure the medial longitudinal arch. The talcum powder was sprayed on a pre-prepared plate. The subject was asked to usually walk a few meters away from the plate and place his foot on the plate as he passed. Staheli index was assessed by dividing the narrowest point of the midfoot in the widest point of the heel was obtained from foot print (Staheli et al., 1987).

Core Stability: In order to measure core stability, the McGill tests were applied, including modified Beiring Sorensen test, Trunk flexor test, and Side bridge test. McGill et al. reported reliability of 0.93–0.98 for these tests (McGill et al., 1999). Given to movement, all portion of the core stability work as a single integrated unit. Consequently, the total time of these three tests was recorded as a single “total core” value (Nesser et al., 2009).

Modified Beiring Sorensen: For this purpose, the subject was lying down in prone while the pelvis was parallel to the edge of the treatment table. Straps were used to fixing the subject's legs and pelvis in the examining table. The subject's used their hands to support their body, which was on a chair in front of the examining table until they were prepared to take their hands off the table and keep a horizontal position. The subjects were asked to maintain the in a horizontal position their trunks as long as possible. Finally, total time that the subjects were able to keep the mentioned position until their hands touched the chair in front of them was recorded in seconds as each subject score (McGill et al., 1999).

Trunk flexor test: For this test, subjects were asked to sit on the testing table and lean their upper extremity against a 60-degree wedge which placed behind them. The subject asked flexed knees and hips joints to 90°. The arms were across on the chest while each hand was placed on the opposite shoulder under the straps. Subjects were instructed when supporting wedge was pulled back 10 cm to maintain the upper body position as long as they can. When the upper body touches, the supporting wedge examiner ended the test (McGill et al., 1999).

Side bridge test: Side bridge test was performed while the subjects were lying in the examination table in side bridge position. Legs were extended, and for providing enough support, the top foot was placed in front of the lower foot. Subjects used one elbow and then lift up their hips off the floor so, they have only two points of reliance on the ground and put head to toes in a straight line. The other arm was held on the chest in an across position with the hand placed on the opposite shoulder. The failure occurred when the subjects lost the straight posture or, the hip returned to the examination tabl (McGill et al., 1999).

2.5. *Dynamic knee valgus*

For evaluation of DKV, a series of single-leg squat tasks was performed. During this task, participants were in a single-leg stance position. They squatted until knee flexion approximately 60° (the necessary instruction to achieve the target flexion angle was given to all subjects by the examiner), and rhythm for this task was 2 s for both descending and ascending phases. Subjects did not receive any feedback or were not taught techniques to perform trial successfully. To perform a successful trial, the participant was asked (1) to maintain a proper testing position; (2) to squat until the target flexion angle ($55° < \text{flexion} < 65°$); (3) to complete the task predetermined rhythm (2 s for descending phase and 2 s for ascending phase); (4) not to touch down by swing foot; (5) legs were not in contact with together; (6) to maintain the heel in contact with the ground (Mauntel et al., 2014). Participants were barefoot throughout testing sessions because shoes could have altered foot position and subsequently altered the proximal segments and joints positioning. This methodology allowed for an accurate portrayal of the individuals' correct biomechanics while minimizing the influence of external sources. Furthermore, if the participants were not barefoot, shoes could confound the results of the study, as the same as all participants wouldn't wear the same shoes (Mauntel et al., 2014).

Three-dimensional trajectory kinematics data for DKV were measured using a 6-camera motion analysis system (Vicon; Oxford Metrics LTD, Oxford, UK). Reflective markers were attached on anatomical landmarks according to the Plug-in Gait method. Trajectory data were sampled at 240 Hz and digitally recorded using Nexus software (Windows Version 2.6.1). Kinematic data were filtered to smooth the acquired coordinate data using a low-pass, zero lag, fourth-order Butterworth filter with a 10-Hz cut off frequency. Subjects were taught to perform a single leg squat task, as previously described. Three trials were collected, and the average of these trails was recorded for each participant.

2.6. *Statistical analysis*

To evaluate whether the variables of interest predicte DKV, a multiple linear regression was used. We performed a univariate analysis for each independent variable with DKV as the dependent variable. Variables that had significant associations with $p < 0.20$ in the linear model analysis were selected for inclusion in the multiple linear regression (Twisk et al., 2005). Variance inflation factor (VIF) was calculated to assess the severity of multicollinearity between independent variables. VIF ($1.21 < \text{VIF} < 2.9$) were acceptable for all variables ($\text{VIF} > 5$ indicated a multicollinearity issue) (Kock et al., 2012).

Descriptive data were presented as means±standard deviations (Dempsey et al., 2007). All statistical analyses were obtained using SPSS statistical software (Chicago, Illinois, v.20). The significant difference was set at $p < 0.05$ and $p < 0.1$.

3. Result

Descriptive statistics of the research variable are shown in Table 1, and the results of univariate analysis for each variable are shown in Table 2.

The results of multiple linear regression are presented in Table 3. The results showed that research variables that entered to the model together predicted 82% of DKV variance ($F(4,26) = 28.09$, $p < 0.001$). Between variables entered in the regression model, the core stability index ($P = 0.001$) and plantar arch index ($P = 0.09$) significantly predicted the variance of the DKV. Results showed that for a one-second reduction in core stability, DKV increased 0.05°. It is also the same as foot arch index (Table 3).

4. Discussion

Specifying variables predicting dynamic knee valgus (DKV) may assist clinicians and researchers in designing knee injury prevention programs more effectively. So the main aim of this study was to determine whether the LEAM and core stability predict DKV during the single-leg squat task. Out of the nine variables investigated in the current study, only two were found as predictors of DKV when performing the single-leg squat. The plantar arch index and core stability index together explained 82% of the variance in the DKV angle during the single squat. The findings of the present study demonstrated that core stability predicted DKV when performing single-leg squat; individuals with decreased core stability showed higher knee valgus during the single-leg squat task.

The DKV is a common faulty movement pattern in the lower extremity, which is a combination of femoral and tibial motions. DKV can be influenced by the proximal and distal joints and segments movements to the knee (Claiborne et al., 2006; Holden et al., 2017; Lee et al., 2014; Sigward et al., 2011). Proper alignment of the pelvis in the frontal plane is essential toward preventing excessive and uncontrol knee valgus during the dynamic task (Kirtley 2006). Abnormal movements of the pelvis or upper extremity can affect the moments acting on the knee joint (Powers 2010). During dynamic and functional tasks such as the single-leg squat, excessive trunk motions, occurring due to insufficient core muscles performance in the frontal and sagittal planes, may produce compensatory adjustments and/or impaired movement to the distal joints to accommodate the lack of pelvic control (Bohdanna T Zazulak et al., 2007). Insufficient core stability control may lead to increased dynamic valgus positioning of the lower extremities (T. E. Hewett et al., 2011). Previous studies showed that decreased trunk musculature performance caused poor control on hip adduction and hip internal rotation when performing weight-bearing functional activities and increased the inclination toward valgus collapse (T. E. HewettFord et al., 2006; van Dieën et al., 2003; Bohdanna T Zazulak et al., 2007).

Hewett et al. (2011) declared that trunk motion could impact on knee abduction by mechanical and neuromuscular mechanisms (T. E. Hewett and Myer 2011). Any laterally movement of the trunk (relative to the stance leg) because of deficit in the core muscle function, can deviate the ground reaction force vector laterally and create a higher lever arm comparative to the knee joint centre (T. E. Hewett and Myer 2011). This deviation might potentially increase knee abduction loading and medial displacement of the knee joint resulting in increased DKV during dynamic movement (T. Hewett et al., 2003; T. E. Hewett and Myer 2011). To counteract the excessive lateral trunk motion and maintain an upright stance and also proper balance, the neuromuscular system increased hip adductor torque by activating hip adductor muscle (T. E. Hewett et al., 1996). This can increase knee abduction moments. According to the mentioned factors, they can increase the knee valgus during a dynamic task such as the single-leg squat.

Table 1
Descriptive statistics of variable.

Variables	Means ± SD
Valgus angle (degree)	18.26 ± 7.46
Plantar arch index(centimeter)	0.82 ± 0.32
Antivertion (degree)	13.52 ± 3.28
Tibial torsion (degree)	6.60 ± 3.69
Hip External rotation (degree)	29.16 ± 6.26
Hip internal rotaion (degree)	30.0 ± 4.58
Tibia vara(degree)	7.93 ± 1.67
Knee hyperextension(degree)	−0.56 ± 1.6
Q angle (degree)	16.95 ± 2.88
Core stability index(second)	303.66 ± 105.92

Table 2
Results of univariate linear regression analysis for each independent variable.

Independent variable	P value
Plantar arch index(centimeter)	0.001[a]
Antivertion (degree)	0.09[a]
Tibial torsion (degree)	0.68
Hip External rotation (degree)	0.49
Hip internal rotaion (degree)	0.43
Tibia vara(degree)	0.35
Knee hyperextension(degree)	0.7
Q angle (degree)	0.1[a]
Core stability index(second)	0.001[a]

[a] Variables entered to multiple linear regression.

Table 3
Results of multiple linear regression for DKV.

Variables	Unstandardized coefficient		T value	sig
	B	SE		
constant	30.07	4.79	6.39	0.001
Plantar arch index(Weiss et al.)	5.08	2.86	1.77	0.09*
Core stability index(second)	−0.05	0.009	−6.01	0.001**

* Significant at $P < 0.1$.
** Significant at $P < 0.05$.

The present results showed that the plantar arch index predicted DKV positively. Subjects with higher plantar arch index (more plantar pronation) had greater knee valgus during a single-leg squat. It is suggested that foot pronation, along with limited ankle dorsiflexion, can play a role in faulty movement patterns such as DKV (Bell et al., 2013). According to the kinematic chain, foot pronation is accompanied by internal tibia rotation (Chuter and de Jonge 2012). As a sequence of foot pronation, limited ankle dorsiflexion and increased tibia internal rotation result in biomechanical compensations at knee increased knee abduction and adduction and internal rotation of femur, which are the main components of DKV (T. E. HewettMyer et al., 2006). In addition, limited ankle dorsiflexion can be important factor would limit the forward movement of the tibia during deceleration, which results in a compensatory adjustment in frontal plane knee excursion (Sigward et al., 2008) and/or increased DKV during a functional task. Eversion in rearfoot as a component of foot pronation contributes to the tibial abduction that affects the knee valgus angle (Joseph et al., 2008). This hypothesis was supported by the result of McClay et al. study. (McClay et al., 2003), their result showed knee position in frontal plane changed in response to an alteration in the ankle position in the frontal plane during running. Therefore, it appeared that rearfoot eversion contributed to increased DKV when performing a single-leg squat.

In spite of our expectations, the Q angle didn't predict the magnitude of DKV. Theoretically, a greater Q angle may be related to excessive DKV because the greater Q angle can cause the more medial displacement of the knee in the frontal plane (Pantano et al., 2005). Moreover, Pantano et al. (2005) showed that individuals with a larger Q angle (≥17°) compared to subjects who had smaller Q angles (≤8°) did not present a greater DKV during the single-leg squat task (Pantano et al., 2005). They stated that static knee valgus was a better predictor of DKV than Q angle. One possible reason for this can be explained by the measurement of static knee valgus and Q angle. While the upper line/vector in the Q-angle calculation was drawn from ASIS to the patella center, the upper line/vector in the static knee valgus was drawn from the center of hip joint to the patella center.

Interestingly, Park et al. (2011) reported a negative relationship between the Q-angle with DKV and the abduction moment of the knee. They stated that a greater Q angle might result to a decreased abduction moment of the knee as define a moment arm between the centre of the knee joint and the lead to decreases in ground reaction force (Park et al., 2011).

Another potential reason for nonsignificant results in this study may be related to differences in neuromuscular development, which can be one of the contributing factors in faulty movement patterns (i.e., DKV) in the lower extremity (T. Hewett et al., 2003). Nguyen et al. (2011) reported that in contradiction to expectation, they could not find any association between the alignment of lower extremity and activation pattern of hip muscle (Nguyen et al., 2011). Those Authors declared that these results were the cause of compensatory adjustment happening in neuromuscular control subsequence of the static change in lower extremity alignment.

On the other hand, Mizner et al. (2008) stated that individuals could improve their landing kinematics (such as decreased knee valgus) even when they receive brief instruction (can be obtained from training or observing). They stated that the amount of the correction is independent of other contributing factors, such as hip muscle strength (Mizner et al., 2008). The result of Mizner et al. study suggested that the observed pattern can be more related of a “choice” or “learned motor pattern” rather than the real effect of hip muscle strength or LEAM. In the current study, although subjects did not receive any feedback or instruction for single-leg squat, the time given to the subjects for practising and preparation before testing may improve the subjects learning and lead to the nonsignificant results.

4.1. Clinical relevance

- Clinicians and researchers should pay more attention to foot pronation and core stability, as predictor variable for DKV during dynamic tasks.
- A combination of neuromuscular and biomechanical factors can play a role in the occurrence of this DKV
- When screening subject with DKV other potential associated factors should be considerd

4.2. Limitations

We acknowledge that despite good ICC reported, always applying clinical methods for measurement of static alignment of lower extremity using has the potential for lack of consistency. Future studies may consider other potential associated factors with DKV, including differences in neuromuscular development, the deficit in lumbopelvic and lower extremity muscle activation pattern, and muscle strength.

5. Conclusions

The findings of the present study showed that the plantar arch index and core stability predicted 82% of the variance for DKV. Clinicians should take these two factors into account when designing prevention and treatment programs for knee valgus.

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CRediT authorship contribution statement

Esmaeil Mozafaripour: Conceptualization, Methodology, Software, Writing – original draft, preparation. **Foad Seidi:** Supervision, Project administration. **Hooman Minoonejad:** Visualization, Investigation, Supervision. **Seyed Hamed Mousavi:** Software, Writing – review & editing. **Mohammad Bayattork:** Data curation, Investigation.

Declaration of competing interest

None of the authors has competing interest declared.

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