

# Sex-related Left Ventricle Rotational and Torsional Mechanics by Block Matching Algorithm

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## ABSTRACT

**Background:** The aim of the present study was to evaluate how left ventricular twist and torsion are associated with sex between sex groups of the same age.

**Materials and Methods:** In this analytical study, twenty one healthy subjects were scanned in left ventricle basal and apical short axis views to run the block matching algorithm; instantaneous changes in the base and apex rotation angels were estimated by this algorithm and then instantaneous changes of the twist and torsion were calculated over the cardiac cycle.

**Results:** The rotation amount between the consecutive frames in basal and apical levels was extracted from short axis views by tracking the speckle pattern of images. The maximum basal rotation angle for men and women were  $-6.94^{\circ} \pm 1.84$  and  $9.85^{\circ} \pm 2.36$  degrees (p-value = 0.054), respectively. Apex maximum rotation for men was  $-8.89^{\circ} \pm 2.04$  and for women was  $12.18^{\circ} \pm 2.33$  (p-value < 0.05). The peak of twist angle for men and women was  $16.78 \pm 1.83$  and  $20.95 \pm 2.09$  degrees (p-value < 0.05), respectively. In men and women groups, the peak of calculated torsion angle was  $5.49^{\circ} \pm 1.04$  and  $7.12 \pm 1.38$  degrees (p-value < 0.05), respectively.

**Conclusion:** The conclusion is that although torsion is an efficient parameter for left ventricle function assessment, because it can take in account the heart diameter and length, statistic evaluation of the results shows that among men and women LV mechanical parameters are significantly different. This study was mainly ascribed to the dependency of the torsion and twist on patient sex.

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## Keywords

Echocardiography; Heart Ventricles; Rotation; Torsion; Motion; Algorithm

## Introduction

The rotational motion of left ventricle (LV) was explained by Leonardo da Vinci in the 16th century for the first time [1, 2]. Richard Lower found that the myocardial contraction is similar to ‘the wringing of a linen cloth to squeeze out the water’ in his studies of myocardial contraction in 1669 [3, 4]. This wringing motion could be explained by a special and complex helical structure of heart myofibers [5].

In normal heart, due to the orientation of left ventricle myofibers and its helical architecture, the base rotates clockwise during systole and the

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apex rotates counterclockwise (as seen from the apex). LV apex and base rotate in opposite directions leading to an LV systolic wringing motion in cardiac systole phase referred to as twist or torsion. In particular, LV twist was defined as the net difference in the rotation angles between apex and base along LV longitudinal axis; whereas, LV torsion is LV twist normalized to the distance between LV apex and LV base (LV length) expressed in degrees per centimeter. Some researchers define LV torsion as the axial gradient in rotation angle multiplied by the average of the outer radii of apical and basal levels. In other words, this definition would be appropriate to compare LV wringing motion of different heart sizes [5-9]. LV twist stores potential energy during the systolic phase that is rapidly released during LV untwisting. In addition, LV untwisting is essential in diastolic filling which can be an important parameter for diastolic suction [10, 11].

Changes in both regional and global LV functions can lead to changes in LV rotation and torsion. Because of differences in LV volume and shape in different ages and sexes, torsion can be changed by the age and sex [12, 13]. Some diseases can cause changes in regional and global LV functions [14-16].

## Material and Method

### Study Population

Twenty one healthy subjects (11 men and 10 women, mean age:  $30.2 \pm 5$  and  $29.1 \pm 4$ , respectively) were recruited in the present cross-sectional study. These participants were selected through random sampling. The inclusion criteria were; healthy subjects with no history of coronary artery disease, arrhythmia, conventional risk factors and not using any medication. All study participants had normal physical examination, ECG and resting echocardiography. All subjects provided their informed written consent prior to their participation in the study. Echocardiographic exams

were performed in all subjects.

### Echocardiography

Two-dimensional (2D) conventional echocardiographic imaging was done with commercial Philips IE33 (Philips Ultrasound, Bothell, WA, USA) using transthoracic sector transducer with harmonic capability. The images were acquired with the volunteers lying in the left lateral decubitus position with holding their breath, by the same operator. Two-dimensional ECG was superimposed on the images, and end-diastole was considered at the onset of QRS in ECG. Two dimensional (2D) echocardiographic imaging was performed using standard parasternal short-axis as well as apical two and four-chamber views according to the guidelines of the American Society of Echocardiography [17].

For each volunteer, LV basal and apical levels were scanned in short axis views using the frame rate between 50–80 frames per second throughout three or four cardiac cycles. The basal and apical levels in the short-axis view were defined based on the anatomic landmarks which were mitral valve at the base and no papillary muscle visible, at the apical level [18]. The information obtained was stored digitally in cine-loop format on the ultrasound machine memory drive and transferred to a personal computer for subsequent processing.

### Block Matching (BM) Algorithm

Block matching (BM) algorithms are the most popular methods because they are effective and simple for implementation. A BM method assumes that the movement of pixels within a defined region or kernel of the current frame can be matched with a region in the previous frame [19-21].

Because the block matching process in whole image is time-consuming and error-prone, in order to save time and avoid incorrect matches, the search area for finding the best-matches should be typically constrained to a searching window around the reference

block. The size of the search region is defined by the maximum expected displacement from frame to frame. It is assumed that all speckle patterns in a block have the same position rather than each other in deferent frames. Another assumption is that tissue movements are in the same and small single plane.

In this procedure, the motion vector is obtained by minimizing the sum of absolute differences (SAD) produced by the kernel of the current frame over a determined search window around the reference block from the previous frame. The motion vector is estimated from the relation between the gray-level gradient of the image and the gray-level difference between images [22, 23].

For motion estimation between the consecutive frames, the BM algorithm approximates and evaluates motion vector by a displacement  $d = (d_x, d_y)$  that finds the best block matching among image regions at different times. For this purpose, a pixel  $X_1 = (x_1, y_1)$  in a reference image  $I_1(x, y, t)$ , a patch  $P_n$  (block of pixels) was chosen centered at  $(x_1, y_1)$  and composed of  $n \times n$  pixels. Then, we tried to find the best correlations of this patch in the successive image  $I_2(x, y, t + \delta t)$  by minimizing the following cost function (SAD) among the search area [1]. With this motion estimation algorithm, the

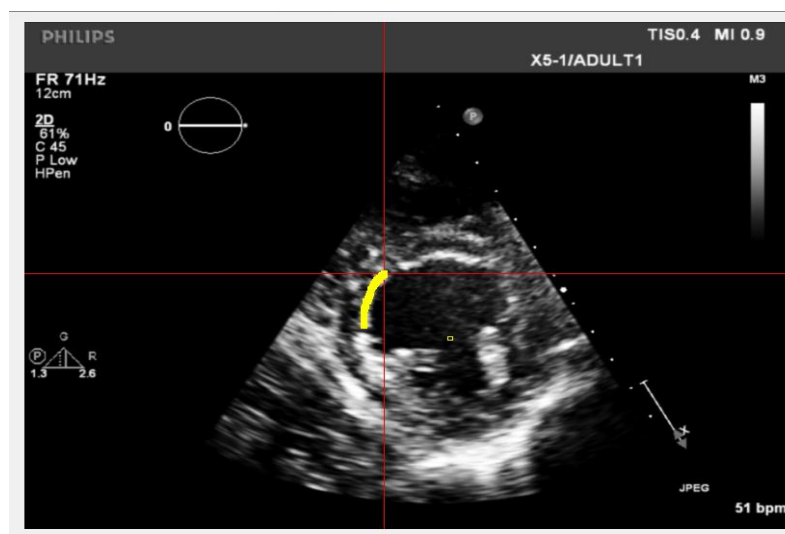
best match will occur when the maximum of similarity is found [24].

$$SAD(X_1, d) = \sum_{i=-n}^{i=n} \sum_{j=-n}^{j=n} |I_1(x_1+i, y_1+j, t) - I_2(x_1+i+d_x, y_1+j+d_y, t+\delta t)|$$

Where  $n$  represents more region(s) of interest (ROI) dimensions,  $I_1, I_2$  are the brightness intensity in the sequential frames, when ROI moved in the horizontal and vertical directions. To perform the block matching algorithm, we wrote a code allowing us to select a ROI by clicking on the myocardial wall and move in desired trace to choose some points as the kernel center. Then we ran the BM algorithm for the selected points. For this purpose, the DICOM images were transferred to a PC and then converted to AVI movies without compression and extracted the first frame to JPG format to determine the ROIs in the first frame as Figure 1. Because the image quality is crucial for accurate BM, we wrote the code in the way that allows us to reject the poor quality points tracking visually and omit them. So, we only consider the best tracking or only take in account the high quality image points.

### LV Twist and Torsion

2D speckle tracking method should be used for the measurement of LV twist to track left



**Figure 1:** The yellow region shows different ROI points in the first frame that is used as the center of kernel for block matching algorithm running.

ventricle motion in two LV short-axis planes at the base and the apical levels. Reliable speckle tracking analysis needs high quality grey-scale images with an optimal frame rate between 50-80 frames. Hence, the parameters such as the sector size and imaging depth that directly affect the imaging frame rate need to be adjusted so that they enable us to reach as possible as high frame rate imaging.

At first, in this analytical study, for calculating base and apex rotation, the center of LV in the base and apex planes was determined. Then, more than 10 points on the myocardial wall were selected and the algorithm was run 10 times. The x, y displacement was calculated and stored in the computer hard drive for base and apex planes separately. The image coordinate was transferred to the point that was selected as LV center, and consequently all x and y transferred to the new coordinate system. In the new coordinate system, the angle between the positive x-axis and the point given by the coordinates (x, y) was computed.

The rotation angle between two sequential frames is the subtraction of the angle between the positive x-axis and the point given by the coordinates of the ROI center ( $x_i, y_i$ ) and ( $x_{i+1}, y_{i+1}$ ). To calculate LV twist, the rotation angle in base and apex levels should be mea-

sured by the way mentioned above, then the twist will be calculated by the following formula:

$$\varnothing = \theta(t)_{apex} - \theta(t)_{base}$$

Whereas  $\theta(t)_{apex}$  is the apex rotation,  $\theta(t)_{base}$  is the base rotation in degrees.

Torsion is defined by the normalized twist angle to the distance between LV apex and LV base. Torsion formula is [25]:

$$\varphi = \frac{(\theta(t)_{apex} - \theta(t)_{base}) * (R_{apex} + R_{base})}{2D}$$

Whereas  $R_{apex}$ ,  $R_{base}$  is the radius of the apex and base in the end diastolic frames and D is the distance between base and apex levels.

### Statistical Analysis

Some statistical tests such as Kolmogorov-Smirnov (K-S) test were conducted to assess normal distribution of values, and Levene's was done to assess homogeneity of variance. The paired sample test was done to compare the mean of basal and apical rotations in two groups and also twist and torsion.

### Results

The demographic and echocardiographic measurements of subjects are illustrated in mean  $\pm$  standard deviation in Table 1. The images that did not meet inclusion criteria were

**Table 1:** Demographic and Echocardiographic Measurements

Variable	Men	Women	P value
Age(y)	30.2 $\pm$ 5	29.1 $\pm$ 4	0.314
Weight(kg)	88.4 $\pm$ 12	53.7 $\pm$ 8	0.000
Height(cm)	176 $\pm$ 4	160.8 $\pm$ 6	0.000
BMI(kg/m <sup>2</sup> )	27.4 $\pm$ 2.5	21.7 $\pm$ 2.5	0.003
Diastolic blood pressure( mmHg)	123 $\pm$ 5	115 $\pm$ 5	0.595
Systolic blood pressure mmHg(mmHg)	80 $\pm$ .1	78 $\pm$ 3	0.526
LVED Basal D (mm)	44.42 $\pm$ 8	40.4 $\pm$ 5	0.000
LVED Apical D (mm)	32.8 $\pm$ 6	29.6 $\pm$ 6	0.000
Basal Rotation (degree)	-6.94 $\pm$ 1.84	-8.89 $\pm$ 2.04	0.054
Apical Rotation (degree)	9.85 $\pm$ 2.36	12.18 $\pm$ 2.33	0.002
LV Twist (degree)	16.78 $\pm$ 1.83	20.95 $\pm$ 2.09	0.002
LV Torsion (degree)	5.49 $\pm$ 1.23	7.12 $\pm$ 1.38	0.000

excluded. The remaining volunteers had adequate data for both apical and basal slices. All volunteers were the same considering their age and physical characteristics such as heart rate, body mass index (BMI) and systolic and diastolic blood pressure.

All variables are presented as mean $\pm$  Standard deviation.

For two groups (men and women), the block matching algorithm was performed to estimate the base and apex rotations. Moreover, LV twist and torsion were calculated. The results show the instantaneous changes in the rotation, twist and torsion angles in the short axis view for men as Figure 2 and women as Figure 3. The maximum of apical and basal rotations in two groups (men and women) are shown in Figure 4, and the peak of twist and torsion in Figure 5.

The measured mean and standard deviation of systolic rotation magnitude for the basal and apical short axis were evaluated by speckle tracking technique.

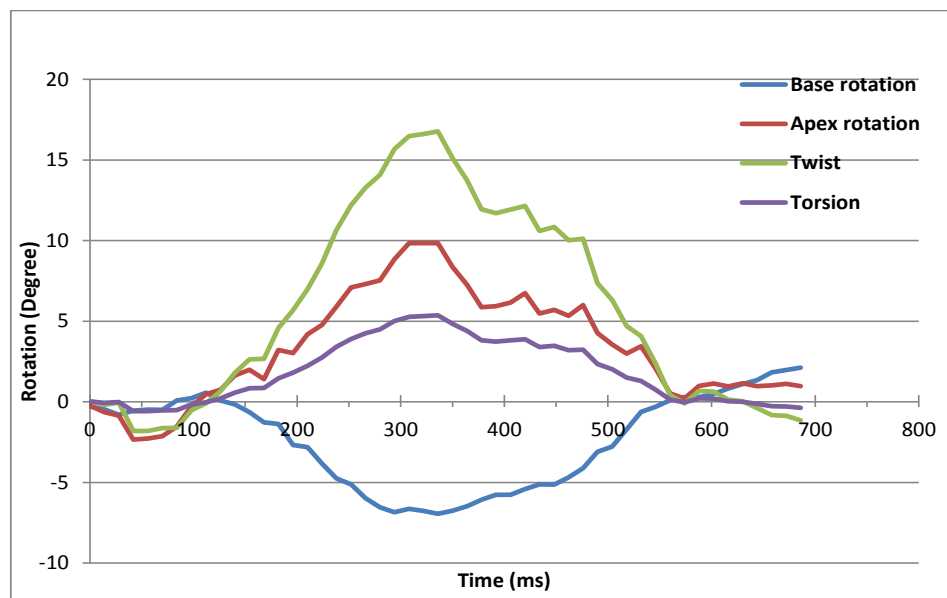
Basal and apical peak rotation angle was clockwise by  $-6.94^{\circ}\pm 1.84$  and counterclockwise  $9.85^{\circ}\pm 2.36$ , respectively for men, and  $-8.89^{\circ}\pm 2.04$  and  $12.18^{\circ}\pm 2.33$ , respectively

for women.

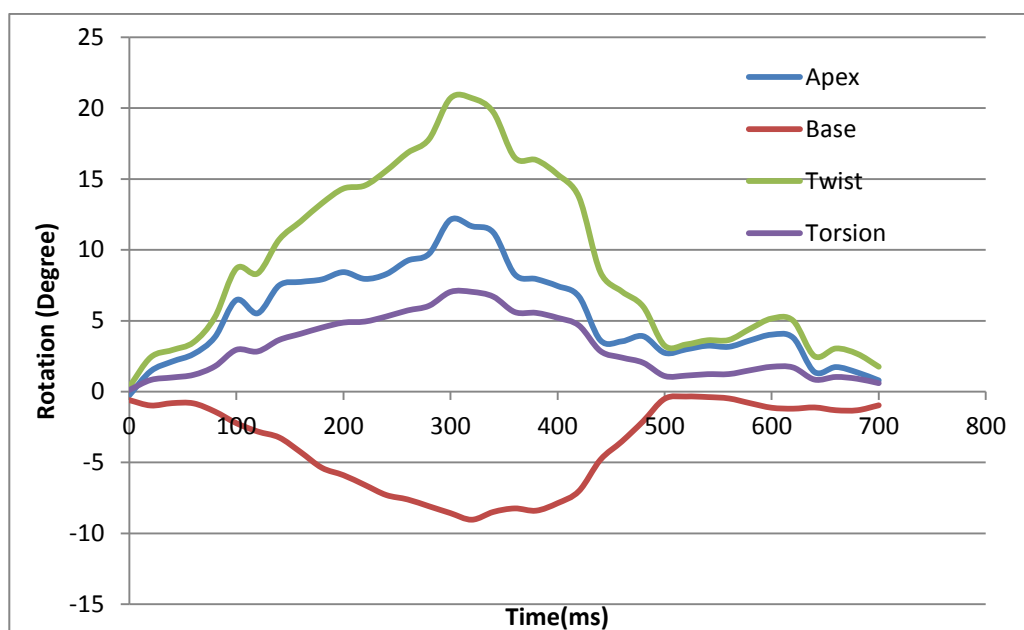
The mean and standard deviation of the maximum rotation angles of the basal and apical levels and LV torsion angle in the short axis view are shown in Figure 4 for healthy men and women subjects.

## Discussion

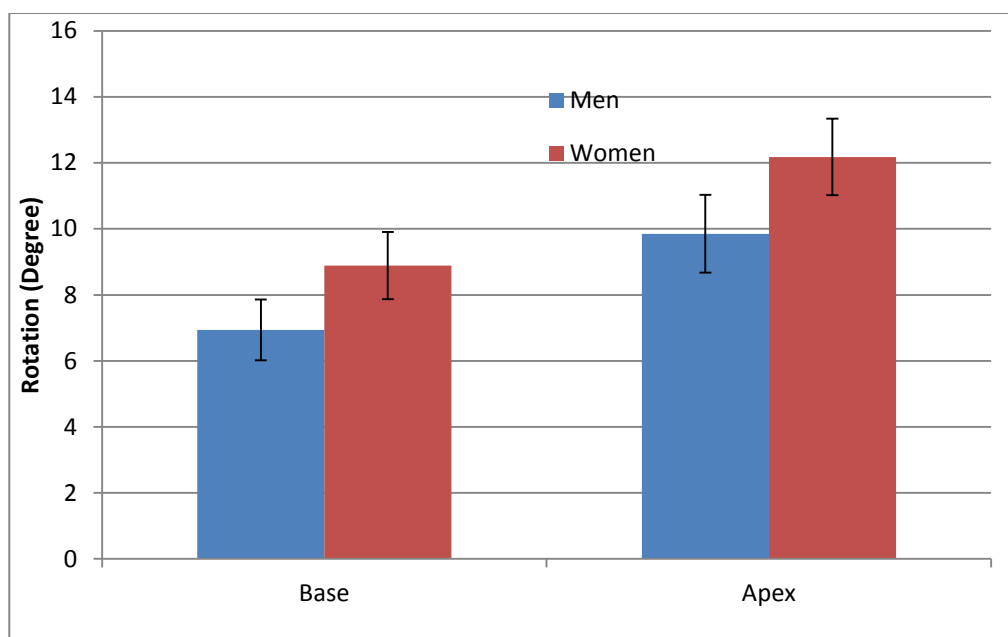
Left ventricular twist and torsion are important biomechanical parameters that have been investigated by different researchers around the world. The torsion parameter can be changed by the changes in LV geometry. The changes in preload, afterload and contractility could affect the LV torsion peak occurrence; hence, extraction of LV torsion is a cornerstone parameter of systolic function and dysfunction [26], and can be a marker of abnormal function and the stage of a heart disease [27]. Some invasive methods were introduced before STE and tagged MRI to assess the LV rotational mechanic (e.g. implanting metal markers on heart and track the motion of the implanted markers in animals and transplanted human hearts by biplane cine radiography: sonomicrometry) [24, 28]. New development in imaging modalities was enabled investigators



**Figure 2:** Rotation of LV Basal and Apical Angles and Twist and Torsion Angles (Degree) for Men



**Figure 3:** Rotation of LV Basal and Apical Angles and Twist and Torsion Angles (Degree) for Women

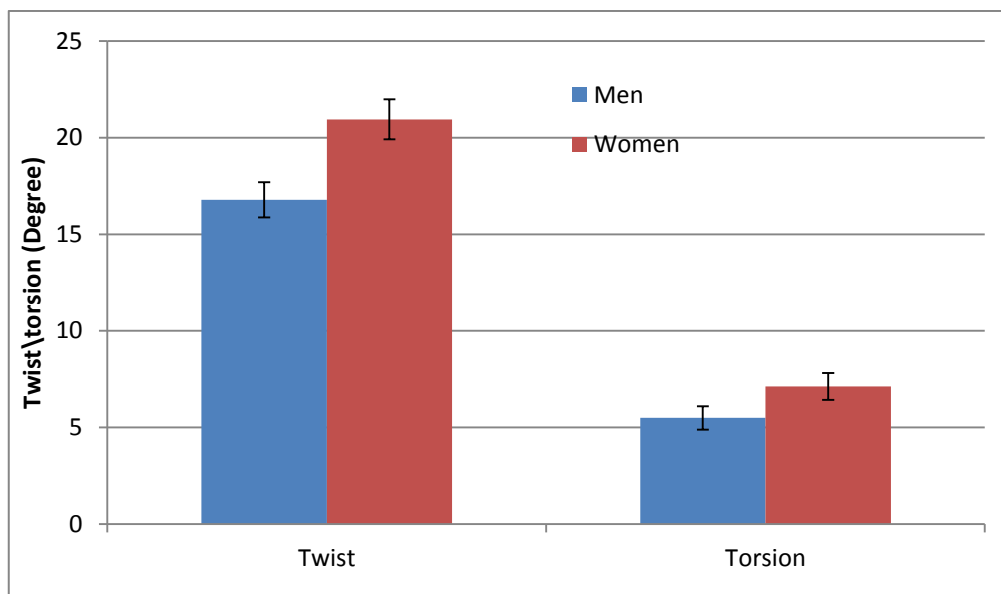


**Figure 4:** Basal and Apical Maximum Rotation in Two Groups

and researchers to measure and quantify left ventricle torsional mechanics with good accuracy. For several years, MRI was considered as noninvasive method of the heart biomechanics measurements. An important limitation with

MRI is the impossibility of routinely studying patients, especially the patients who have a pacemaker and/or an internal cardioverter-defibrillator [10].

Because of wide availability of echocardi-



**Figure 5:** Basal and Apical Maximum Rotation in Two Groups

graphic facilities, echocardiography is a more feasible and cost-benefit technique for assessment of LV mechanics rather than MRI, particularly for patients with a pacemaker and/or internal cardioverter-defibrillator. An early application of assessing twist by echocardiography was the semiquantitative study of rotational motion of papillary muscles [29]. Tissue Doppler Imaging (TDI) is another way for assessing LV rotation [30]. The advantage of TDI is that the myocardial velocity can be detected directly and continuously among several cardiac cycles with high temporal resolution. Some studies have shown that LV rotational velocities can be measured by TDI with higher temporal resolution than MRI [31]. The disadvantage of TDI method is its angle dependency of acquired myocardial velocity data [32].

2D echocardiographic method is an angle independent method for motion estimation which is based on 2-dimensional speckle. These speckles are created by the constructive and destructive interference of ultrasound beams backscatter from anatomical structures smaller than the wavelength of ultrasound [33]. The accuracy of this method has been

validated against sonomicrometry and tagged MRI [33, 34]. In this process, high image quality leads to high quality tracking. Hence, tracking is concisely sensitive on the image quality and is capable mismatch of motion tracking. But, to enhance image quality before running of the block matching algorithm, we imbedded a Gaussian filter to remove noises. Furthermore, we wrote the algorithm in the way that user can see the tracking process for every point that is selected for tracking and can reject or accept the quality of tracking. Then, the rotation angles will be computed on the acceptable tracking points. The method introduced here for motion estimation is based on 2-dimensional echo tracking using time domain processing which provides conditions in which motion estimation is not angle-dependent or cardiac-translation dependent. There are some conditions that should be provided to achieve the goal of good motion estimation successfully and make this approach usable. High-quality second-harmonic images should be used while image acquisition, the images should be acquired at frame rates higher than 50frames/s, and the images should be stored in

DICOM format.

According to the results of this study, twist and torsion in women were higher than men. Other heart parameters such as LV ejection fraction and wall elasticity were investigated and shown that women have higher LV ejection fractions [35-37] and greater systolic elasticity than men. This difference shows that in women myocardial contractility is greater than men [36, 37]. It has been shown that LV twist and torsion can be affected by LV end-systolic and end-diastolic LV volumes, in other words, it is dependent on LV size. Hence, because of having adequate cardiac output, hearts with smaller ventricles should have greater torsion. On the other hand, LV twist and torsion directly are related to LV fiber orientation, and LV fiber orientation is dependent on LV shape [13, 38-40].

The limitations of this study were: the poor endocardial definition of 2-dimensional echo image, through-plane motion of basal and apical planes and the frame rate limitation because of its dependency on depth and sector angle. In spite of these limitations, we measured the twist and torsion angles for the LV short axis view. To account for differences in heart size, torsion was calculated based on the basal and apical maximum radii, and the distance between the apical and basal levels.

## Conclusion

In the present study, left ventricle basal and apical rotational mechanics were analyzed by 2D BM algorithm to quantify twist and torsion angles. The statistic evaluation of results shows that between men and women groups LV mechanical parameters are significantly different.

Tracking is a non-invasive and utilizing method for motion estimation in left ventricular through cardiac cycle. This study emphasizes that torsion angle seems to be an appropriate biomechanical parameter to be used for evaluating heart function rather than twist. For both twist and torsion significantly depends

on the sex. This study was mainly ascribed to the dependency of torsion and twist on patient sex.

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## Conflict of Interest

None

## References

1. Kendoul F, Fantoni I, Nonami K. Optic Flow-Based Vision System for Autonomous 3D Localization and Control of Small Aerial Vehicles. *Unmanned Aerial Vehicles: Embedded Control*. 2010:209-36.
2. STONE W. Starling's Principles of Human Physiology. *American Journal of Physical Medicine & Rehabilitation*. 1953;**32**:390.
3. Gunther R. Early Science in Oxford. Oxford: Oxford University Press. 1920.
4. Geleijnse ML, Van Dalen BM. Let's twist. *European Heart Journal-Cardiovascular Imaging*. 2008.
5. Greenbaum RA, Ho SY, Gibson DG, Becker AE, Anderson RH. Left ventricular fibre architecture in man. *Br Heart J*. 1981;**45**:248-63. doi.org/10.1136/hrt.45.3.248. PubMed PMID: 7008815. PubMed PMID: 482521.
6. Henson RE, Song SK, Pastorek JS, Ackerman JJ, Lorenz CH. Left ventricular torsion is equal in mice and humans. *Am J Physiol Heart Circ Physiol*. 2000;**278**:H1117-23. PubMed PMID: 10749705.
7. Nakatani S. Left ventricular rotation and twist: why should we learn? *J Cardiovasc Ultrasound*. 2011;**19**:1-6. doi.org/10.4250/jcu.2011.19.1.1. PubMed PMID: 21519484. PubMed PMID: 3079077.
8. Bertini M, Sengupta PP, Nucifora G, Delgado V, Ng AC, Marsan NA, et al. Role of left ventricular twist mechanics in the assessment of cardiac dyssynchrony in heart failure. *JACC Cardiovasc Imaging*. 2009;**2**:1425-35. doi.org/10.1016/j.jcmg.2009.09.013. PubMed PMID: 20083079.
9. Torrent-Guasp F, Kocica MJ, Corno AF, Komeda M, Carreras-Costa F, Flotats A, et al. Towards new understanding of the heart structure and function. *Eur J Cardiothorac Surg*. 2005;**27**:191-201. doi.org/10.1016/j.ejcts.2004.11.026. PubMed PMID: 15691670.
10. Beladan CC, Calin A, Rosca M, Ginghina C, Popes-



- cu BA. Left ventricular twist dynamics: principles and applications. *Heart*. 2014;**100**:731-40. doi.org/10.1136/heartjnl-2012-302064. PubMed PMID: 23661636.
11. Notomi Y, Martin-Miklovic MG, Oryszak SJ, Shiota T, Deserranno D, Popovic ZB, et al. Enhanced ventricular untwisting during exercise: a mechanistic manifestation of elastic recoil described by Doppler tissue imaging. *Circulation*. 2006;**113**:2524-33. doi.org/10.1161/CIRCULATIONAHA.105.596502. PubMed PMID: 16717149.
  12. Notomi Y, Srinath G, Shiota T, Martin-Miklovic MG, Beachler L, Howell K, et al. Maturational and adaptive modulation of left ventricular torsional biomechanics: Doppler tissue imaging observation from infancy to adulthood. *Circulation*. 2006;**113**:2534-41. doi.org/10.1161/CIRCULATIONAHA.105.537639. PubMed PMID: 16717154.
  13. Yilmaz S, Kiliç H, Demirtas S, Çakar M, Edis L, Vatan M, et al. Age-related changes in left ventricular torsion. *Atherosclerosis*. 2015;**241**:e214-e5. doi.org/10.1016/j.atherosclerosis.2015.04.1015.
  14. Burns AT, McDonald IG, Thomas JD, Macisaac A, Prior D. Doin' the twist: new tools for an old concept of myocardial function. *Heart*. 2008;**94**:978-83. doi.org/10.1136/hrt.2007.120410. PubMed PMID: 18625792.
  15. Leitman M, Lysyansky P, Sidenko S, Shir V, Peleg E, Binenbaum M, et al. Two-dimensional strain-a novel software for real-time quantitative echocardiographic assessment of myocardial function. *J Am Soc Echocardiogr*. 2004;**17**:1021-9. doi.org/10.1016/j.echo.2004.06.019. PubMed PMID: 15452466.
  16. Sengupta PP, Khandheria BK, Narula J. Twist and untwist mechanics of the left ventricle. *Heart Fail Clin*. 2008;**4**:315-24. doi.org/10.1016/j.hfc.2008.03.001. PubMed PMID: 18598983.
  17. Henry WL, DeMaria A, Gramiak R, King DL, Kisslo JA, Popp RL, et al. Report of the American Society of Echocardiography Committee on Nomenclature and Standards in Two-dimensional Echocardiography. *Circulation*. 1980;**62**:212-7. doi.org/10.1161/01.CIR.62.2.212. PubMed PMID: 7397962.
  18. Luo X, Cao T, Li Z, Duan Y. A preliminary study on the evaluation of relationship between left ventricular torsion and cardiac cycle phase by two-dimensional ultrasound speckle tracking imaging. *Int J Cardiovasc Imaging*. 2009;**25**:559-68. doi.org/10.1007/s10554-009-9462-1. PubMed PMID: 19415523.
  19. Cuevas E, Zaldívar D, Pérez-Cisneros M, Oliva D. Block-matching algorithm based on differential evolution for motion estimation. *Engineering Applications of Artificial Intelligence*. 2013;**26**:488-98. doi.org/10.1016/j.engappai.2012.08.003.
  20. Sun F-R, Wang X-J, Wu Q, Yao G-H, Zhang Y. Measurement of left ventricular torsion using block-matching-based speckle tracking for two-dimensional echocardiography. *Journal of Electronic Imaging*. 2013;**22**:013010. doi.org/10.1117/1.JEI.22.1.013010.
  21. Mobasheri M, Mokhtari-Dizaji M, Roshanali F. Estimating the Myocardium's Angle of Three-Dimensional Trajectory, Using the Tracking of Sequential Two-Dimensional Echocardiography Images. *J Cardiovasc Ultrasound*. 2014;**22**:14-22. doi.org/10.4250/jcu.2014.22.1.14. PubMed PMID: 24753804. PubMed PMID: 3992343.
  22. Mondillo S, Galderisi M, Mele D, Cameli M, Lomoriello VS, Zaca V, et al. Speckle-tracking echocardiography: a new technique for assessing myocardial function. *J Ultrasound Med*. 2011;**30**:71-83. PubMed PMID: 21193707.
  23. Philip JT, Samuvel B, Pradeesh K, Nimmi N, editors. A comparative study of block matching and optical flow motion estimation algorithms. Emerging Research Areas: Magnetics, Machines and Drives (AICERA/iCMMMD). 24-26 July 2014. Kottayam: Annual International Conference on; 2014. doi: 10.1109/aicera.2014.6908204.
  24. Liangbao J, Jiao C, Rui C, Xuehong C, editors. A hierarchical block matching algorithm in depth extraction for binocular vision. 21-23 February 2011. Seoul: Proceedings of the 5th International Conference on Ubiquitous Information Management and Communication; 2011. doi: 10.1145/1968613.1968760.
  25. Lumens J, Delhaas T, Arts T, Cowan BR, Young AA. Impaired subendocardial contractile myofiber function in asymptomatic aged humans, as detected using MRI. *Am J Physiol Heart Circ Physiol*. 2006;**291**:H1573-9. doi.org/10.1152/ajp-heart.00074.2006. PubMed PMID: 16679404.
  26. Takeuchi M, Otsuji Y, Lang RM. Evaluation of left ventricular function using left ventricular twist and torsion parameters. *Curr Cardiol Rep*. 2009;**11**:225-30. doi.org/10.1007/s11886-009-0032-x. PubMed PMID: 19379643.
  27. Reyhan M, Wang Z, Li M, Kim HJ, Gupta H, Lloyd SG, et al. Left ventricular twist and shear in patients with primary mitral regurgitation. *J Magn Reson Imaging*. 2015;**42**:400-6. doi.org/10.1002/jmri.24811. PubMed PMID: 25408263.
  28. Kendoul F, Fantoni I, Nonami K. Optic flow-based

- vision system for autonomous 3D localization and control of small aerial vehicles. *Robotics and Autonomous Systems*. 2009;**57**:591-602. doi.org/10.1016/j.robot.2009.02.001.
29. Schiros CG, Desai RV, Venkatesh BA, Gaddam KK, Agarwal S, Lloyd SG, et al. Left ventricular torsion shear angle volume analysis in patients with hypertension: a global approach for LV diastolic function. *J Cardiovasc Magn Reson*. 2014;**16**:70. doi.org/10.1186/s12968-014-0070-4. PubMed PMID: 25316384. PubMed PMCID: 4177166.
30. Axel L, Dougherty L. MR imaging of motion with spatial modulation of magnetization. *Radiology*. 1989;**171**:841-5. doi.org/10.1148/radiology.171.3.2717762. PubMed PMID: 2717762.
31. Biering-Sorensen T, Jensen JS, Pedersen S, Galatius S, Hoffmann S, Jensen MT, et al. Doppler tissue imaging is an independent predictor of outcome in patients with ST-segment elevation myocardial infarction treated with primary percutaneous coronary intervention. *J Am Soc Echocardiogr*. 2014;**27**:258-67. doi.org/10.1016/j.echo.2013.11.005. PubMed PMID: 24325959.
32. Dragos AM, Abate E, Pinamonti B. Advanced Echocardiographic Techniques in Arrhythmogenic Right Ventricular Cardiomyopathy. *Clinical Echocardiography and Other Imaging Techniques in Cardiomyopathies*: Springer; 2014. p. 159-64.
33. Notomi Y, Lysyansky P, Setser RM, Shiota T, Popovic ZB, Martin-Miklovic MG, et al. Measurement of ventricular torsion by two-dimensional ultrasound speckle tracking imaging. *J Am Coll Cardiol*. 2005;**45**:2034-41. doi.org/10.1016/j.jacc.2005.02.082. PubMed PMID: 15963406.
34. Opdahl A, Helle-Valle T, Skulstad H, Smiseth OA. Strain, strain rate, torsion, and twist: echocardiographic evaluation. *Curr Cardiol Rep*. 2015;**17**:568. doi.org/10.1007/s11886-015-0568-x. PubMed PMID: 25676830.
35. Natori S, Lai S, Finn JP, Gomes AS, Hundley WG, Jerosch-Herold M, et al. Cardiovascular function in multi-ethnic study of atherosclerosis: normal values by age, sex, and ethnicity. *AJR Am J Roentgenol*. 2006;**186**:S357-65. doi.org/10.2214/AJR.04.1868. PubMed PMID: 16714609.
36. Williams A, Shave RE, Stembridge M, Eves N, editors. Females have greater left ventricular twist mechanics than males during acute reductions to preload. *Am J Physiol Heart Circ Physiol*. 2016;**311**:H76-H84.
37. Chung AK, Das SR, Leonard D, Peshock RM, Kazi F, Abdullah SM, et al. Women have higher left ventricular ejection fractions than men independent of differences in left ventricular volume: the Dallas Heart Study. *Circulation*. 2006;**113**:1597-604. doi.org/10.1161/CIRCULATIONAHA.105.574400. PubMed PMID: 16567580.
38. Adhyapak SM, Parachuri VR. Architecture of the left ventricle: insights for optimal surgical ventricular restoration. *Heart Fail Rev*. 2010;**15**:73-83. doi.org/10.1007/s10741-009-9151-0. PubMed PMID: 19757029.
39. Hassaballah A, Hassan M, Mardi A, Hamdi M. Modeling the effects of myocardial fiber architecture and material properties on the left ventricle mechanics during rapid filling phase. *Appl. Math*. 2015;**9**:161-7. doi.org/10.12785/amis/090121.
40. Von Deuster C, Stoeck CT, Genet M, Atkinson D, Kozerke S. A reference dataset of in-vivo human left-ventricular fiber architecture in systole and diastole. *Journal of Cardiovascular Magnetic Resonance*. 2015;**17**:Q112. doi.org/10.1186/1532-429X-17-S1-Q112.