Biomechanical Effect of Forearm Flexor Muscles depending on Handle Sizes

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수공구 손잡이 형태에 따른 생체역학적 영향도 분석

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Abstract

수공구 사용시 과도한 힘은 작업성 근골격계 질환을 일으킬 수 있는 주요 원인중 하나이다. 이와 관련하여, 수공구 파지시 인체 내부에 부과되는 근력과 외적으로 작용된 힘 간의 비율을 이해하는 것이 중요하며, 이는 근육에 부과되는 과도한 힘을 최소화 시키고, 작업에 필요한 힘의 효율성을 극대화 시키는데 필수적이라 할 수 있다. 이러한 비율과 관련하여 많은 연구가 되어 왔으나, 대부분 수리적 인체역학적 모델과 같은 간접적 추정 방법에 의거하고 있는 실정이다. 이러한 인체역학적 모델을 검증하고 개선하기 위하여 해부용 팔 (cadaver)을 활용한 직접적인 근력과 악력 측정이 필수적이다. 본 연구에서는 이러한 해부용 팔을 이용하여 상지 굴근(hand flexor)을 자동으로 제어하고 근력과 함께 악력을 측정할 수 있는 Hand Motion Simulator를 개발하고, 이를 통하여 다양한 사이즈의 손잡이 파지시 요구되는 근력과 외적으로 적용된 악력을 비교함으로써 수공구 손잡이 사이즈에 따른 근력의 효율성에 대하여 측정을 해 보았다. 또한, 적용된 굴근 (FDP & FDS) 간의 힘 비율에 따른 파지법의 차이를 조사해 보았다. 내부에 주어진 근력은 외부로 작용된 악력보다 5.3배 높은 부하가 작용하였으며 이러한 수공구 손잡이 파지시 힘의 효율성 역시 FDP 와 FDS 간의 비율이 3:2 였을 때, 그리고 손잡이 크기가 작을수록 높은 결과를 보였다. 반대로 손잡이의 크기가 커질수록 힘의 효율성은 저하되었다. 또한, 손가락 관절 각도의 경우 FDP와 FDS간의 비율에 따라 상이한 자세를 나타내었다. FDP 굴근의 비율이 높을 경우 손가락 끝마디 관절 (DIP) 의 굴곡을 보였으며, FDS 굴근 비율이 높을 경우 손가락 두 번째 관절(PIP)의 굴곡을 보였다. 본 연구를 통한 결과는 추후 상지작업자에 대한 근골격계 질환 예방 기준안 마련 및 수공구 설계를 위한 기초자료로 활용이 가능할 것으로 보인다.

Keywords : Biomechanics, Flexor muscle, Handle size

1. INTRODUCTION

Considering internal impacts in designing a hand tool is crucial to reduce harmful effects on users. These effects are associated with a series of musculoskeletal disorders (MSDs) such as hand tendonitis, strained muscles, and carpal tunnel syndrome (NIOSH, 2001). Thus, forceful exertion of the upper extremities is widely recognized as one of the physical risk factors associated with the development of upper extremity work related musculoskeletal disorders (WRMSDs) which are of increasing concern to employers as a source of worker compensation claims, lost work time and reduced productivity (NRCIM, 2001).

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For quantifying peak exertion intensity with hand tools, biomechanical modeling of the hand is important for understanding how exerted forces act on the internal tissues for various hand functions. The National Institute for Occupational Safety and Health (NIOSH) has been supporting the development and validation of models for the quantitative assessment of exposure to ergonomic risk factors including forceful exertion (NIOSH, 2001). However, the mechanisms leading to risk of WMSDs have not been identified. Quantitative mechanical hand modeling has been considered since the early 1960s (Landsmeer, 1961) and has increased in complexity (An et al., 1979; Valero-Cuevas et al., 1998; Kong, 2001). Some extensive studies included all known intrinsic and extrinsic muscles involved in grasp (Chao et al., 1989; An et al., 1979; Valeo-Cuevas et al., 1998; Li et al., 2001). Although anatomically precise, these models are challenging to implement in practice, since they require input parameters that are often difficult or impossible to measure. Assumptions regarding muscle recruitment and optimization methods sometimes produce results that have been found inaccurate (Dennerlein et al, 1998).

Electromyography can investigate muscle activation patterns (Darling et al., 1994; Dennerlein et al., 1998), but this method yields only an estimate of muscle activation, as many motor units may be active).

The most reliable assessment of the effects of external loading conditions on tendon forces is obtained by directly measuring tendon forces in human body. Direct measurement of tension in the tendon provides a measure of forces within the human musculoskeletal system that have been earlier predicted by isometric force models. Validating the mathematical models by experimental measurement in vivo was undertaken in previous researchers (Schuind et al. 1992; Dennerlein et al., 1998; Kursa et al, 2005). However, Schuind et al. did not record finger joint positions, while Dennerlein et al. measured force in only one tendon. In addition, Kursa et al.(2005) measured force in only one finger. Also, in vivo test, true tendon forces are probably lower than the predicted results because these experiments were performed during carpal tunnel surgery. In such case, the muscles are partially inactive and weaken pinch and power grip forces (Chao, 1989).

Therefore, cadaveric experiments make no limitation of finger motion and measuring extrinsic muscles. Cadaveric studies have focused on the flexor tendon forces in both tip pinch and power grip actions (Bright and Urbaniak, 1976) or the relationship between tendon pulley integrity and flexor tendon excursion (Armstrong et al., 1978; Idler et al., 1986; Lin et al, 1990). Also, Brand et al. reported the relative tension capacities of forearm and hand muscles with cross-sectional area of the muscles in cadaver hand (1981). However, no method has solved the force ratio between the tendon force and the externally applied force in power grip motion with various handles. In addition, no simultaneous comparison of kinematic data with tendon forces exists in the literature of power grip.

The objective of this study was to investigate an optimal handle size minimizing internal tendon loads and maximizing external grip forces with a cadaver model. We hypothesized that a small diameter handle has higher grip force than larger diameter handles on the same tendon force. For the hypothesis, a hand motion simulator: a cadaver model was developed to investigate hand biomechanics of power grip motion and examine grip force and finger force distribution of the hand generated by extrinsic flexor muscles (FDP and FDS). Moreover, the interaction effect of tendon force ratio (FDP to FDS) with finger joint motion was also investigated with the cadaver model using various sizes of cylindrical handles to find optimal handle size.

2. MATERIALS AND METHODS

2.1 Hand Motion Simulator

The Hand Motion Simulator (HMS) was built to generate flexor tendon forces and simulate hand motions and postures with a cadaver hand. Muscle forces generated by two linear actuators with force feedback control were applied to the tendons of the extrinsic muscles of the hand. The HMS was composed of five essential parts: frame supporting a specimen, motion delivery unit through stepper motor driven linear actuators applying forces to the muscle tendons, data acquisition unit for force transducers measuring internal and external forces, and operating program to control the HMS. We previously validated the simulator with a force feedback control through the comparison between desired forces and actual tendon forces generated by the hand motion simulator (Park, 2009).

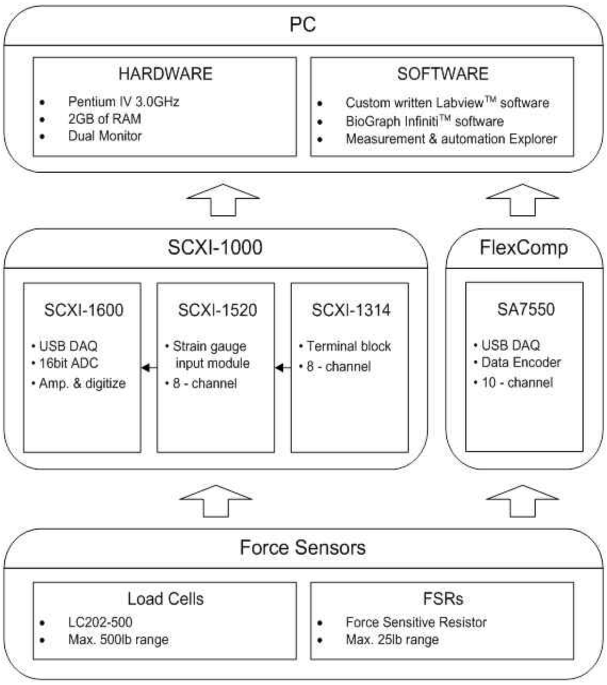

Figure 1. Data acquisition system for the hand motion simulator

A data collecting system was utilized to measure external forces and internal forces while grasping. External forces were defined as grip force measured from a force transducer inserted in a split cylindrical handle, and internal forces were determined as tendon forces taken by force transducers in line with the force delivery unit. The data acquisition system was designed for measuring internal and external forces coupled with force feedback control system (Fig. 1).

2.2 Specimen

One female fresh-frozen human cadaveric left hand speci-men was used in this study. The specimen was amputated at the middle humerus and was free from apparent musculo-skeletal disorders and anatomical abnormalities. After thawing overnight at room temperature, the specimen was minimally dissected to expose the musculotendinous junctions of the extrinsic muscles. The specimen was prepared with the entire forearm below the elbow joint and mounted into the Hand Motion Simulator after the preparation. Since we only focused on flexor muscles among the extrinsic muscles, flexors of the extrinsic were grouped into each tendon. The flexor digitorum (FDP) and the flexor digitorum superficialis (FDS) were the main finger flexor muscles and were selected to simulate the power grip motion. To maintain the structure of interior tissues including muscles, tendons and vascular system, only the FDP and FDS were extracted and isolated from the other muscles in the forearm and other tissues left undisturbed. The wrist fixator maintained a functionally neutral wrist angle of 20° extension allowing free motion for all fingers (Li, 2001). Each flexor tendon separated from flexor muscles was securely coupled with a freeze clamp (Sharkey, 1995) and coolant tubes for liquid nitrogen were connected to the freeze clamps.

2.3 Methods

Two flexor muscle forces (FDP and FDS) and five different handle sizes were the independent factor for an analysis of variance (ANOVA) procedure. FDP force was fixed at 100N, and FDS force increased from 20N to 100N by 20N at once. Hence, the total tendon force was also increased as the FDS force increased. Grip force generated by pulling internal flexor tendons was the dependent variable of each condition. Three trials were run for each five different handles and five different tendon force ratios, with three minutes intervals between each trial. All of the 15 trials (5 tendon force ratios x 3 trials) were completely randomized for each handle. A sequence of five handles was also randomized as 45, 60, 47, 30 and 37mm. Grip forces were measured by a force transducer inserted in handles. Two-way ANOVA was used to evaluate effects for grip forces across five handle sizes and tendon forces conditions. Significant effects were further explored using Tukey's pair-wise comparisons. The significance level was set as 0.05. Statistical analyses were performed in the statistics toolbox of Minitab 13.0 (Minitab Inc., State College, PA, USA).

3. RESULTS

3.1 Handle size analysis

The relationship between the internal tendon force and the external grip force was analyzed to assess the effect of different diameter handle sizes. The number of handle from 1 to 5 represents 30mm, 37mm, 45mm, 50mm and 60mm cross-sectional diameter, respectively.

3.1.1 Data summary

Figure 2 presents the grip force variations with the box plots on each handle. The grip force for the smallest handle size was 20% (significant at $p < 0.05$) larger than the mean grip force and 23% lower force than the mean grip force for the largest handle size. The reason that there were high variations of the grip force in Figure 2 was that the average grip force derived from different tendon force ratios. Thus, we need to analyze the interaction effect of handle and nominal internal force with separated tendon force ratios.

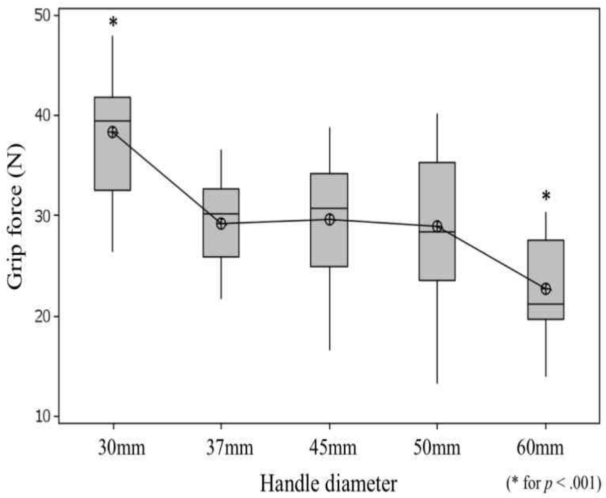

Figure 2. Main effect of grip forces on handle sizes

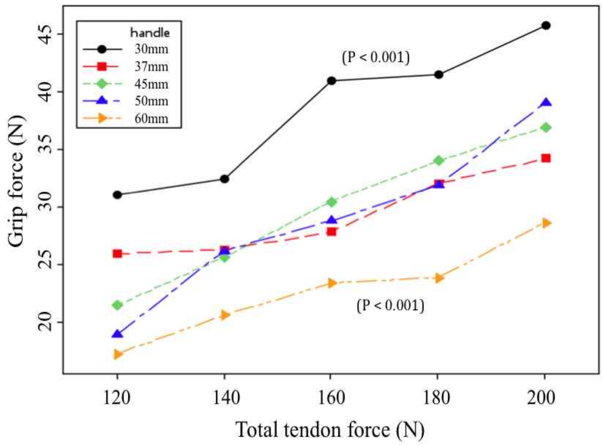

Figure 3. The interaction of tendon forces and handle sizes

3.1.2 Optimal handle size

The graph in Figure 3 shows clearly which handle had the highest grip force within each internal force level. Since the ANOVA output did not suggest an interaction effect between nominal internal force and handle size, we only need to check which handle has the highest grip force overall and also handle size effect was analyzed with all levels of internal force. The handle effect was that handle 1 having significantly higher grip forces than the other handles (p-value compared with other handles are <0.001); handle 5 also had significantly lower grip force than the other handles. Handle 2,3, and 4 are not significantly different from each other. Consequently, the smallest (30mm) handle diameter had maximum grip force, and it was the optimal handle size among five different diameter handles at least for this size hand. As shown in Table 5.5, the grip force was highest in the smallest handle (30mm) with highest grip force and the efficiency of internal tendon force (4.2F), for an external grip force F, was highest with the smallest handle as well. The largest diameter handle (60mm) had lowest grip force and worst tendon force efficiency (7.0F).

3.2 Tendon force ratio in Grip force

The relationship of two flexor tendon forces on different sizes of handles was analyzed to find the effect of different FDP and FDS ratios. Figure 4 shows the relationship between the grip force and the internal force as internal forces increase. FDP forces were always constant (100N) and FDS forces were increased from 20N to 100N. Thus, the internal force increase was due exclusively to increasing FDS tendon force. As shown in Figure 4, the mean grip forces increased linearly as the internal force increased, and it seems that the slope of grip force was constant. That means that the ratio between the FDP and FDS does not affect grip force. Hence, we need to analyze the tendon force ratio effect on each handle in detail.

To find the relationship between the tendon force ratio and grip force on different sizes of handle, Analysis of Covariance (ANCOVA) was used to solve the hypothesis. Figure 5 shows the result of ANCOVA. Both handle type and relative FDS% have significant influence on grip force ($p < 0.001$). Moreover, the interaction of handle and relative FDS% is also significant with p-value <0.012. This term tests the hypothesis that the slopes of each regression line between relative FDS% and grip force are equal across five handle types. Its significance suggests that the regression lines of five handle types do not have identical slops. The relationship between relative FDS% and grip force are different across five handles. Hence, we need to investigate this further for subtle differences.

Since regression lines for five handles did not have equal slopes, to get the regression slope of each handle type, we can split the dataset based on handle types and conduct regression analysis of each handle size. The output suggests that the relationship between relative %FDS and grip force were all significant (p-value of the relative FDS% coefficient is <0.001) but the slopes (relative FDS% coefficient) are not identically the same. Handle 2 and 5 apparently have a slope that is much flatter (regression coefficient 0.269 and 0.343, respectively) than other handles whose regression coefficients are at least 0.5.However, when the model order of regression was plotted with the quadratic, the slope of each handle increased as relative FDS% increase. Especially, this was noticeable at 40-50% of relative FDS%, most slopes of handles were drastically increased (see Figure 6). This means that relatively higher FDS tendon force (40% to 50%) yielded a better grip force during the power grip motion. This result agrees with the study of mechanical characteristics of a muscle (Brand and Hollister, 1981). They analyzed the FDP and FDS characteristics with the mass, average fiber length and cross-sectional area of all fibers. Based on the mass fraction (%) of the FDP and FDS, the ratio of two tendons was 3:2. In addition, the tension fraction (%) ratio of two tendons showed 3:2.3 profundus to superficialis tendon force ratio. The findings indicate that the physical FDS had 20%~30% less force than the FDP. Thus, their study showed that the slope of grip force increased with 35%~50% FDS of the total internal force.

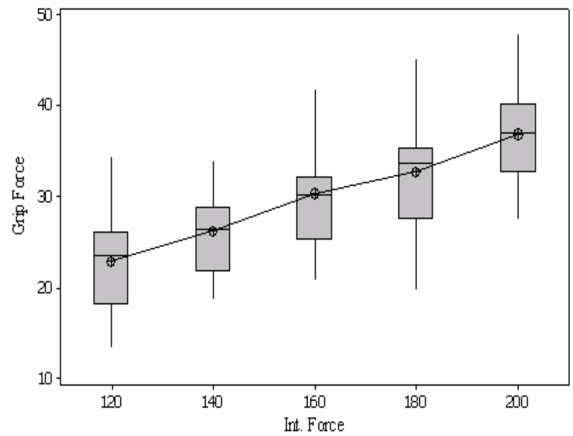

Figure 4. The effect of the tendon force ratio between the FDP and FDS

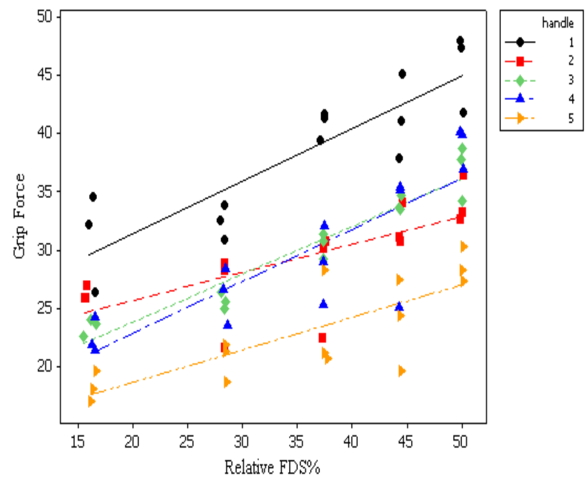

Figure 5. The interaction between the relative FDS percentage and the handle size

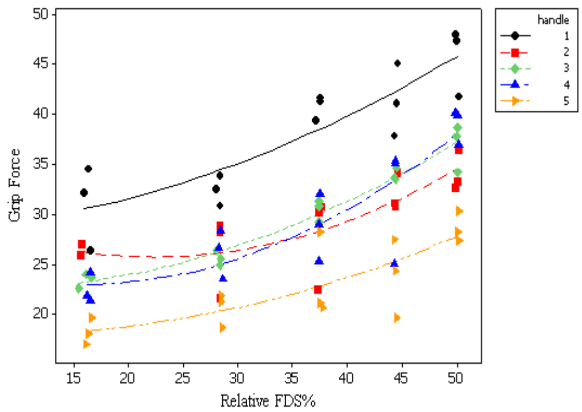

Figure 6. The interaction between the relative FDS percentage and the handle size

3.3 Finger joint angle analysis

The finger joint angles were generated by a custom developed program by Labview for measuring the interphalangeal joint angles (Table 5.12). The effect of handle, the relative percentage of FDS force (%FDS) and the interaction of handle and %FDS were all significant (p <0.001). Figure 5.15 shows the captured grip postures representing finger joint angles in lateral view depending on different tendon force ratios and handle sizes. The main effects on DIP, PIP and MCP joint angles due to different handle sizes and the relative FDS forces (%FDS) are plotted in Figure 5.16.

In terms of handle size, the joint angles at the MCP and PIP joint showed a descending pattern as the handle diameter increased, but DIP joint angle showed convex pattern according to handle size increasing. Essentially, flexions of MCP and PIP joint decreased as the handle size increased, but the DIP joint angle was most flexed for the middle handle size.

The loading of the tendon forces with different ratio (FDP vs. FDS) produced different finger joint motions. According to increasing the percent FDS force from 10% to 50% of total tendon force, on average, the MCP joint angle gradually increased from 19.7° to 23.8°; in contrast, the PIP joint angle showed a rapid rise from 70.1° to 83.4° in the high proportion of FDS while the DIP joint angle displayed a rapid decline from 32.8° to 2.7°. These results clearly show that the tendon force ratio of FDP to FDS affects the finger joint motion while grasping a handle. Higher percent FDP force with less FDS force produced flat PIP joint angles and flexed DIP joint angles; In contrast, the same proportion of FDP to FDS force (i.e. PDF : PDS = 1 : 1) produced flexed PIP joints and flattened DIP joints. Thus, the DIP would be too flexed with low portion of FDS force compared with FDP force, and would be too flat with same level of FDS to FDP force. Therefore, 3:2 FDP to FDS tendon ratio that already concluded before can be supported by this mechanism of finger joint angles by different tendon force ratios.

Table 1. Finger Joint Andlge flexion on %FDS and handle

Handle		1			2			3			4			5	
%FDS	MCP	PIP	DIP	MCP	PIP	DIP	MCP	PIP	DIP	MCP	PIP	DIP	MCP	PIP	DIP
50%	33.5°	98.9°	0.1°	37.2°	89.4°	4.4°	23.2°	79.2°	5.7°	11.1°	83.1°	-3.7°	14.0°	66.2°	9.4°
40%	34.9°	93.9°	8.8°	35.0°	90.6°	10.4°	19.7°	64.3°	13.6°	11.7°	81.1°	0.2°	14.7°	71.0°	10.1°
30%	35.7°	80.3°	23.6°	30.8°	89.8°	24.0°	12.1°	66.9°	30.7°	11.4°	73.1°	9.2°	10.5°	78.2°	9.9°
20%	33.1°	76.8°	34.1°	31.7°	84.0°	34.9°	8.4°	61.0°	47.7°	13.9°	67.0°	16.4°	14.5°	67.2°	12.0°
10%	32.6°	75.2°	38.4°	31.8°	80.2°	42.1°	6.6°	69.0°	52.3°	15.5°	55.5°	16.7°	15.1°	62.1°	14.1°

4. DISCUSSION

We analyzed grip forces on different handle sizes. These grip force presented the effect of handle diameter on power grip motion. There was a negative relationship between handle diameter and grip force, which showed that the grip force decreased from 38.3 to 23.0 N, as the cylindrical handle diameter increased from 30 to 60mm. Thus, the highest grip force was generated on the smallest handle size (30mm), and the lowest grip force was on the largest diameter handle (60mm). This finding supports our hypothesis and it is straightforward and consistent with other studies (Edgren et al., 2004; Seo and Amstrong, 2008). Edgren et al. (2004) also found the inverse relationship of handle size and grip force measured by a cylindrical gauge dynamometer like a split handle with a force transducer used in this study. Seo and Amstrong (2008) measured split cylinder grip strength decreased with increasing ratio of handle diameter to hand length and hand size. Kong and Lowe (2005) presented that the total finger force, which was defined as the sum of all phalangeal segments showed a significant inverse relationship with handle diameter as the fingers were more extended to grasp larger handles, but they measured the finger force distribution with thin profile resistive force sensors on each phalange instead of using a split handle dynamometer.

The efficiency of internal forces to external forces was compared to understand the mechanisms of hand disorders and the relationship between the finger tendon forces and the externally applied forces to the handles and the fingers. In terms of hand sizes, the average internal tendon force of the smallest handle size (30mm) was, for external grip force F, 4.2F and the largest handle showed 7.0F of the force efficiency. Also, the mean efficiency of the internal forces to the external forces was 5.3F. In other words, the force efficiency was significantly decreased as the cylinder diameter increased.

The contribution of this study was to validate the mathematical model and analyze the mechanism of hand flexor tendons in power grip function. Thus, tendon force ratio and efficiency of grip force were analyzed by measuring grip force with split cylindrical handles. Also, those results were compared with finger joint angle and the prediction model. Despite of several limitations, the results of this study provide novel insights into the direct measurement of internal impact of flexor tendons generated by power grip motion. The knowledge of the kinetic outcome of tendon forces could be used for designing an optimal hand tool, and planning of diagnosis and treatment modalities of the hand problem.

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