足踝矫形器及其生物力学研究进展

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摘要 足踝矫形器是以非手术方法解决足踝问题的穿戴器具,可以有效控制足踝位置及运动,减缓关节负载。概述了足踝问题及相关足踝矫形器分别对人体的生物力学影响,探讨了计算生物力学的功能和在足踝矫形器评估中的初步应用。由于足踝生物力学的复杂性和研究技术的局限性,足踝矫形器的设计目前仍主要依据于经验,产品的治疗或康复效果存在很大争议。随着临床影像学以及测量技术和计算生物力学技术的发展,足踝生物力学研究能够更深入全面提供足踝内部和外部的受力环境,并广泛应用于足踝矫形器的设计和评估中。基于此,辅助以3D打印等先进制造技术,足踝矫形器将实现舒适性和功能性兼备的快速个性化定制,在具有良好的矫正效果的同时,其制造周期和成本将大大降低。

关键词 足踝矫形器; 足踝生物力学; 足踝损伤; 关节应力

1 足踝问题对人体的生物力学影响

1.1 关节活动能力

足踝问题会影响人体关节的运动范围,导致人体运动功能受限。足部畸形患者,在静态站立和运动过程中,关节运动角度和受力情况与正常人会有差异。扁平足在站立时,足底与地面全接触或几乎全接触,后足明显外翻。与正常人相比,正常行走中扁平足测试者的前足外展角度增加[1],后足外翻角度增加[2-3]。足部关节运动的异常会直接影响踝关节的背曲角度[4]。与扁平足相反,高弓足患者足底与地面接触面积减少,跖骨区足底压力增加[5],站立时造成足内翻,而在实际步态中中足和后足外翻角度减小[6]。高弓足的双脚因体重分布不均,走路方式容易外旋、稳定度差,会影响下肢的力学轴线,导致下肢运动或关键受力异常[7]。拇外翻也是常见的足部畸形问题。拇外翻畸形主要指拇趾在第一跖趾关节处向外侧偏斜移位,在成年人中的发病率

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为23%[8]。研究发现,拇趾外翻患者第一跖骨相对于第二跖骨的平均内旋角度高于正常人[9]。同时,踝关节背屈角度在站立相末期小于正常人[10],导致外翻力的增加,加剧拇外翻的进程[11]。同时,足踝软组织疾病如足底筋膜炎、踝关节软骨损伤也会影响足踝的运动。与正常人相比,足底筋膜炎患者的后足外翻角度大。站立相初期前足跖屈角度、前足内外翻角以及第一跖趾关节的背屈角度更大[12]。踝关节炎患者在前足、中足及后足运动角度与正常人都存在显著差异[13]。足踝部位的骨折也会影响足踝部位的正常活动,导致行走障碍。

1.2　肌肉

人体运动的产生主要通过肌肉驱动来完成,足踝部位的畸形或损伤反过来会影响肌肉的几何特性及生理活性。扁平足患者的腓骨长肌和胫骨前肌肌腱厚度增加,跟腱厚底降低[14],足内部肌肉如趾短伸肌、长伸肌、拇展肌体积增加,小指展肌减小。肌肉的生理结构改变会导致足部关节运动异常,如前足外展角度增加[15]。扁平足患者的小腿三头肌及跟腱的张力过大会进一步影响中足应力,造成足踝不稳定[16-17]。成年高弓足的产生主要与足踝部位的肌肉不平衡有关。对于高弓形足患者,胫后肌和腓长肌的强度会大于胫前肌和腓短肌,进而会导致后足内翻和前足外翻,影响足部压力分布[18]。拇外翻畸形也会影响肌肉的生理及几何特性。以正常人为参考,患者拇外展肌和拇短屈肌的厚度和横截面积减小[19],同时拇外展肌肌肉活性明显小于拇内展肌肌肉[20]。

1.3　疼痛与关节损伤

足踝与下肢其他关节在运动过程中相互耦合,足踝异常除了对足踝关节造成直接影响,还会影响足踝以上的关节及软组织。由于没有足够的足弓支持,严重的扁平足患者步行时足底部分软组织应力增加,引起足底筋膜炎及后足疼痛[21-23]。下肢力线的改变可能还会引起膝、髋关节、髌骨疼痛及胫骨应力异常,甚至导致脊柱疼痛[7,21,24-28]。Kosashvili等[29]对军人前膝及后背痛与扁平足程度的关系进行了回顾性分析,发现严重扁平足与前膝和后背痛的发生有关。老年人扁平足与膝关节疼痛及软骨损伤的关系的研究发现,扁平足与膝关节炎症状及膝关节内侧软骨损伤有关[26]。高弓足患者后足内翻,导致足部外侧压力过大,从而造成踝关节不稳,腓骨肌腱炎及应力骨折。关节力过大会导致踝关节炎的产生[30]。拇外翻患者在第一跖骨头内侧会出现软组织疼痛和骨头突出,如果不及时进行治疗还可能导致锤状趾或爪趾畸形产生,影响足部压力分布[31-32]。足底筋膜炎是足底的肌腱或者筋膜发生无菌性炎症所致,最常见症状是脚跟的疼痛与不适[33]。足底筋膜炎会导致身体结构和功能的变化包括姿势偏斜、内侧足弓触痛、踝背屈受限、跖屈肌力量减弱、踝内在肌力量减弱、距下关节过度旋前[34]。由肌腱退变、微创伤、炎症、副舟骨及全身系统性疾病等多种原因综合所导致胫后肌腱功能失调,可继发性引起足弓扁平,继而发生后足外翻、中足外展、前足旋前。临床上胫后肌腱功能失调的典型畸形包括后足外翻、前足外展、足纵弓塌陷及随着后足外翻逐渐加重而出现的代偿性前足旋后[35]。

2　足踝矫形器及其生物力学影响

足踝部异常除导致疼痛、畸形及运动障碍外,还可进一步影响膝关节、髋关节、骨盆和脊柱等的正常功能。足踝矫形器是以非手术方法解决足踝问题的穿戴器具。常见足踝矫形器包括鞋垫、足弓支撑、局部足垫、护踝等及类似产品。局部足垫是最简单的矫形器,放置于脚底常用以缓和前足痛。其存在多种样式、形状及大小,如圆形或者环形垫用以减缓胼胝或鸡眼受压。鞋垫放置于鞋子内部,可治疗包括关节炎和扁平足等在内的多种足部问题。市面可购买到多种型号和尺寸的成品来满足需求,特殊需求需要进行个性化定制。其软硬度范围较广,最终目的为预防或矫正足部功能异常或畸形,为人体提供稳固的基底支撑。但矫形鞋垫置入鞋内后改变鞋子支撑状态,可能引起疼痛或者应力增加,通常需要进行局部调整和适应期才能与鞋子成为一个整体的功能单元。

踝-足矫形器(ankle-foot-orthoses,AFO)主要控制参数为踝关节的运动范围,用于缓解或治疗踝

关节炎、足下垂及肌腱炎等,也可用于长期卧床者保护足踝功能预防肌骨病变。典型的护踝矫形器呈L型,从膝盖下缘覆盖至足部跖骨头。其主要作用是固定关节正常功能位避免韧带异常拉伸,牵拉肌腱对抗肌肉挛缩,以及代偿部分肌无力,适用于控制有各种神经系统或肌骨系统病变引起的足下垂。运动中的足踝矫形器可以提高足踝稳定性,在步态摆动期使脚趾与地面之间保持间隙,降低脚趾拖地引起的摔倒风险。根据制作方法和功能不同,材料可以包括热成型塑料、金属、皮革及碳复合材料。足踝矫形器可使用于从幼儿至老人所有年龄段,是应用最广泛最常见的矫形器。

足踝矫形器作为人体外部辅助设备帮助人恢复或者加强身体局部的结构和功能缺陷,其影响范围包括足踝、下肢、骨盆甚至脊柱。其相关的生物力学参数主要包括关节运动及受力、肢体对线、接触界面应力等,通过调节这些参数改善人体运动的能动性、稳定性和协调性。

2.1 足踝矫形器对足踝的影响

足底支撑类及关节包裹类矫形器对足部的最直接影响是应力分布以及足踝内外反角度。在缓解足底疼痛类问题时,局部足底支撑影响限制在疼痛区域应力分布,对足踝或以上部分的运动影响甚微。治疗足内外翻类问题的鞋底支撑矫形器,如外侧或内侧楔形鞋垫可以影响足踝关节运动和角度,如减小足外翻,甚至足踝以上部分[36-37]。矫形器设计形式、材料和鞋内放置方法不同对足踝生物力学将产生不同影响,也因此在矫形器对后足运动是否造成显著性影响问题上存在争议。通常内侧楔形鞋垫放置在后足区域,配合足弓支撑治疗后跟外翻或过度旋前问题,但近期研究表明,放置在前足或后足都会对过度旋前运动产生影响,前足的旋前会导致后足外翻增加甚至髋关节内转[38]。有数据表明内侧垫放置前足和后足都会减小足外翻角度和速度[39];Nigg等[40]则认为内侧楔形鞋垫仅可以降低旋前初期的足外翻,且后侧放置比前足放置这一效果更加明显;亦有不同观点称后足角度不会影响外翻的角度和时长[41]。骨骼运动的监测受到包裹软组织的影响,矫形器的定量化影响作用并不易通过运动分析精确评估。为了消除软组织的在运动监测时造成的误差,有研究把运动检测点订入骨头替代贴在皮肤或鞋子表面,更加精确和定量化评估了内侧支撑矫形器对后跟外翻和胫骨转动的影响作用[42]。

受定制AFO被广泛用于补偿跖曲肌肉功能,其有效性与产品的弯曲刚度紧密相关,而弯曲刚度的选取则取决于跖曲肌肉的活动度。跖曲肌在步态的支撑期为足踝提供稳定的上提和向前推进的力量,减少踝关节能量损耗[43],尤其在支撑期后期脚跟提起时控制小腿的稳定。当足底与地面全接触时,踝关节是距骨同小腿之间的旋转中心,此时距下关节运动帮助减小踝关节应力。跖曲肌弱化造成小腿失衡,呈现出屈膝步态、步长减小及步速降低等问题。对正常人佩戴AFO进行运动分析发现佩戴者跖曲肌的发力时间被提前,对于病人来讲跖曲肌提前发力并不可行,因此调用其他肌肉用更复杂的机制补偿该跖曲需求[44]。有数据表明,AFO能够增加步态支撑期、足趾离地期以及摆动期的最大背曲量[45],在动力学方面AFO通过增加足底压力中心的路径长度降低了踝关节承载力矩[46]。虽然临床研究证实AFO能够增强患侧承重能力以及改善膝踝运动功能,但尚未充分证明AFO可以改善髋关节运动学及其他关节动力学及肌肉力等[47]。

2.2 足踝矫形器对下肢的影响

膝关节的轴向对线维持关节以上身体垂直方向平衡,其影响因素包括最大内收力矩及冠状面运动,膝关节内收力矩也是影响膝关节载荷的重要参数[48]。外侧楔形鞋垫是非手术方法治疗膝关节炎的重要矫形器之一,其通过调整足部骨头位置以及关节对线来降低膝关节内侧压力。实验发现外侧楔形鞋垫能够减小冠状面膝关节内收力矩[49]从而降低膝关节炎的恶化风险,但关节疼痛缓解作用并不优于普通平垫[50]。如果伴随其他足踝问题,干预方法还有鞋型鞋垫加内侧足弓支撑、单独足弓支撑以及吸震鞋垫。但数据表明,外侧鞋型鞋垫加内侧足弓支撑对冠状面膝关节最大内收力矩并无明显影响,对冠状面踝关节和距下关节有较大影响[51-53]。而单独内侧足弓支撑[54]和单独吸震鞋垫[55]

干预则不会对膝关节内收力矩产生影响。内侧楔形鞋垫用于治疗身体对线异常综合症,数据证明其能够增加膝关节内收力矩和角度,但对膝关节内收的运动学参数无明显影响[56-57]。Meadows在AFO对下肢生物力学影响方向的研究中较为全面阐述了AFO对青少年步态的影响,参数包括了地面反力作用位置和方向及步态周期参数,并指出AFO通过降低膝关节过度伸展和加强髋关节伸展增加了下肢的推进作用[58]。在足跟触地期AFO能够显著减小膝关节内收力矩[49],增加膝关节的屈曲幅度和力矩[49,59],最大屈曲值在单脚支撑期也显著增加[60]。膝关节的最大伸展角度在支撑期有显著性增加,但在摆动期则不产生影响[61]。

足部矫形器对步长、步幅及步态对称性产生显著性影响[62],对小腿肌肉活动产生肌肉活动时段产生影响,但对肌肉活动度的影响作用在很多研究中发现并不明显。由距下关节内翻引起的小腿症状患者在足部矫形器干预下,胫骨前肌、腓骨长肌及腓肠肌在步态过程中的肌电信号发生变化,胫骨前肌的作用时长显著性增加,而三组肌肉的活动度无明显差别[63]。在对下肢痛的缓解治疗研究中,下肢肌肉股二头肌和胫骨前肌的活动度在足部矫形器干预后情况后发生显著性变化,分别降低11.1%和增加37.5%,而内侧腓肠肌、股内肌及股外肌的活动度则无明显变化。在AFO对肌肉活动的影响研究中已经证实AFO能够减少中风康复者的步行期间的能量损耗、增强患侧承重能力以及改善膝踝运动功能,但尚未充分证明AFO可以改善髋关节运动学、及其他关节动力学及肌肉力等[64]。

2.3　足踝矫形器对骨盆及脊柱的影响

足部矫形器对下肢异常生物力学的改变被进一步用以治疗骨盆、脊柱及以上部位的对线或病痛[65]。盆骨向上承接头部和躯干与髋关节相互作用,向下动态连接双侧下肢,是身体对线和运动体系的重要组成部分。盆底肌肉活动的对称性可以影响盆骨对线,进一步引起足底应力分布变化[66],反之亦然,足底压力分布调整优化也有利于盆骨的对称性。足部矫形器被用于治疗人体对线异常综合症,可改变下肢动力学参数来恢复脊柱和骨盆的正常功能和结构[57]。

从临床和理论层面,足部矫形器被认为能够改变疼痛区域肌肉活动度来缓解疼痛,也被作为治疗下腰痛的手段之一。研究已经通过评定疼痛等级的方法证明足部矫形器对下背痛的缓解作用[67]以及提高髋关节外展力矩的对称性[68]。通过测量分析步态过程中背部肌肉的肌电信号,研究人员发现楔形鞋垫对肌肉活动程度没有明显影响,但却可以改变背部肌肉的活动时段[69]。

3　足踝矫形器的计算生物力学研究

足踝矫形器对人体的生物力学影响大多基于实验测量,如步态分析、物理测量、医学影像、尸体实验、组织力学性能测量、界面参数测量等。但足踝矫形器对人体组织的应力分布的影响以及足踝矫形器自身的生物力学特性与矫形器设计直接相关,且通过以上研究手段难以获取数据。因此,计算生物力学方法被广泛用于足踝矫形器的生物力学研究,评估难以物理测量或者参数分析时间相应周期过长的生物力学因素,用以辅助矫形器的制造或者优化设计。计算分析可以对足踝矫形器受力、足踝受力以及矫形器与足踝接触界面的应力分布进行定量分析。对制造材料及形状等设计因素进行参数分析可以无需通过制造测试而快速得到结果相应。

计算生物力学分析方法在足踝矫形器的设计中评估参数一般包含足底应力分布,足踝软组织及关节受力[70]以及矫形器变形和应力分布,例如观测矫形器厚度和刚度对足底应力分布以及足底软组织受力的影响[71]。有研究基于有限元分析方法对糖尿病足矫形器进行优化设计时,分析了足底筋膜区域以及后跟区域足底软组织的应力分布,并发现矫形器侧边与足踝接触间隙显著影响足底软组织的应力分布[72]。不同的生物力学参数对设计的影响作用不同,矫形器表面形状对足底应力分布影响最大,其次是矫形器材料刚度[73]。有研究利用足踝及矫形器有限元模型进行分析发现全接触鞋垫可以降低足跟、跖骨头区域的最大应力值,但增加了

中足区域和大拇趾区域的足底应力[74]。

热塑性AFO存在的一个普遍问题是应力破坏,早在1995年就有研究利用有限元模拟方法分析了AFO使用状态下的应力分布[75],发现应力集中区包括脖颈区、足跟区以及小腿外侧区,但最高应力发生在脖颈区。在特定区域加强设计可以预防断裂,为了确定加强区域及评估加强效果有研究建立了AFO有限元模型并模拟步态支撑期,对比了不同加强方法下AFO的最大拉应力和变形[76]。佩戴AFO会导致局部区域体感过热或出汗问题,改换设计材料时利用有限元模型分析对比不同设计的变形及应力,可以保证其生物力学功效不会降低[77]。为了降低足底应力,需要找出最优化的厚度和材料组合,改变有限元模型中AFO不同层的厚度和材料,分析对足部软组织和骨头传递的拉力的影响作用,可以找出优化的AFO设计明显改善前中后足的应力分布,也因此改善AFO佩戴下的步态[78]。 因为对模型调整修改的快速响应以及对难以测量参数分析的便利性,有限元分析已经作为一个重要环节在AFO制造过程中得以广泛应用[79-80]。

4 结论

足踝是人体运动和承重的最主要部分,其损伤或病变直接影响人体的基本运动功能。足踝矫形器是以非手术方法辅助加强足踝功能、缓解疼痛的有效干预手段,与此同时也会对改变足踝、下肢甚至脊柱的功能或造成继发伤害。因此大量研究评估了足踝矫形器对足踝、下肢及以上部分的生物力学影响。这些数据已成为足踝矫形器优化设计提高治疗有效性的必要条件。

目前,足踝矫形器的设计仍多基于经验,其矫正或康复效果存在广泛争议。随着医学影像技术、实验测量技术及计算生物力学技术的发展,更加深入全面的足踝乃至下肢生物力学技术将被更全面和深刻揭示,且广泛应用于足踝矫形器的设计和评估。人们已开始智能矫形器的研究,在矫形器中加入生物反馈和时时调节功能以及对环境监测提供主动动力、障碍避让等功能。以上研究将促使个性化定制足踝矫形器成为现实,并将大大提高产品的功能性和舒适性。三维打印技术和打印材料的突破将大幅缩短个性化定制足踝矫形器的制造周期。

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Biomechanics of orthoses of the foot and ankle

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Abstract The foot is the most fundamental part of the human body for providing the body support, absorpting the impact and acting with the environment for propelling during movement. The ankle joint serves as a critical connection between the foot and the upper body. The problems in the foot and ankle will cause pain and weaken the functions of certain parts, and potentially result in further negative consequences to the lower limb, the pelvis even the spine. The orthoses of the foot and ankle, including the insoles, the braces, the arch supports and the ankle-foot orthoses, are used as non-surgical treatments to relieve pain, and compensate or retrieve functions. The foot orthoses could redistribute the plantar pressure distribution and realign the segments of the foot and ankle. The changes in the foot and ankle possibly will lead to biomechanical deviations in the upper body. It is critical to enhance the knowledge of the biomechanical consequences for the estimation of the efficiency and the optimization of the design of the foot ankle orthoses.

Keywords orthoses of foot and ankle; ankle-foot biomechanics; foot injuries; joint pressure

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