Nat. Commun.：可拉伸自粘附纯有机干电极及柔性生物电子应用

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生物电信号（如心电（ECG）、肌电（EMG）和脑电（EEG）等）不仅是反映人体健康状况的重要生理指标，也是人机交互界面的生物表面电信号源。可穿戴电极是准确检测这些生物电信号的重要设备。目前普遍使用是一次性的Ag/AgCl凝胶电极，由于溶剂挥发导致的信号衰变和电解质刺激皮肤等问题，这类凝胶电极不适合长期稳定检测生物电信号，也不利于人机界面的持续性稳定信息交互。干电极是一种适于长期检测生物电信号的穿戴式电极，但在文献里报道的干电极与皮肤之间的贴合性较差，尤其是在身体运动和皮肤出汗等状况下，造成明显的信号噪音和运动伪像干扰，限制了干电极的实际性能。

最近，**新加坡国立大学欧阳建勇教授课题组和任洪亮教授课题组合作，首次报道了一种可拉伸、自粘附和高电导的导电高分子生物干电极（PWS干电极）。**他们利用生物可相容性的导电高分子PEDOT:PSS、水性聚氨酯以及山梨糖醇助剂等，通过简便的溶液成膜方法，形成一种具有双连续相结构的复合薄膜电极，同时具有高导电性（>390 S/cm）和高拉伸性（断裂伸长率>43%），并且具有优异的自粘附性能。不仅能贴敷于细微的皮肤纹路，牢固的粘附在干甚至湿皮肤表面，即使在皮肤拉伸变形、震动等状态下，PWS干电极也能保持不脱落。此外，PWS干电极还表现出拉伸应变不灵敏的特点（440次拉伸循环后电阻变化< 6.5%）。

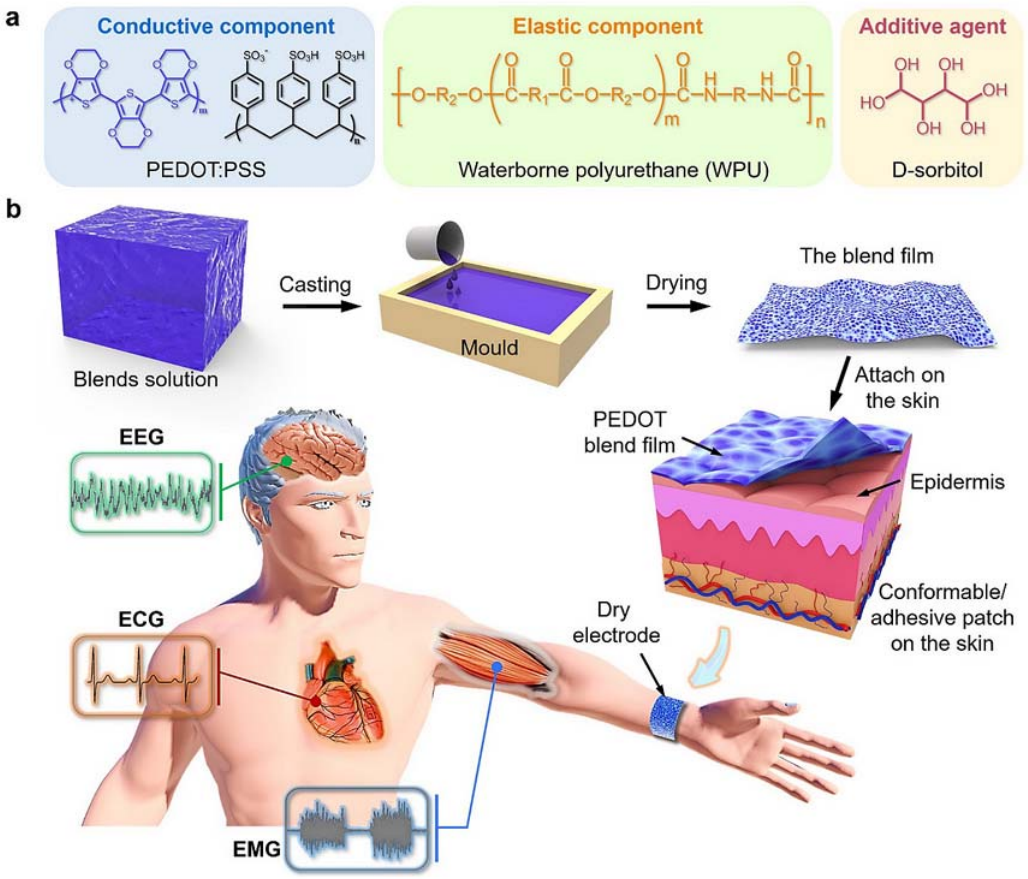

图1. PWS干电极的制备材料(a)、制备过程及其表皮生物电信号检测应用(b)。

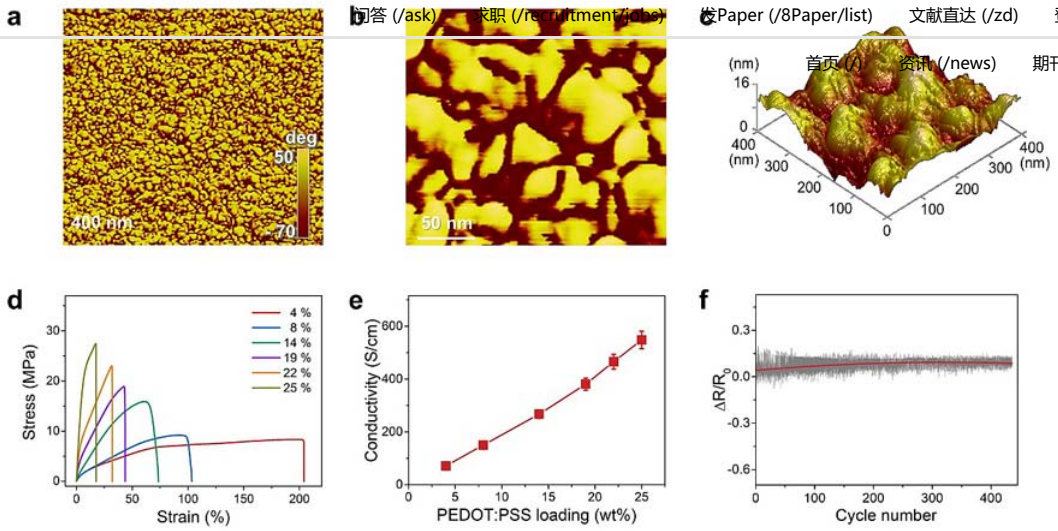

图2. PWS的微观结构及其拉伸、电学性能。a, b PWS干电极薄膜表面的原子力显微镜相图；c PWS干电极薄膜表面的原子力显微镜3D形貌；PWS薄膜的拉伸性能（d）和导电率（e）随着PEDOT：PSS含量的变化；f 440次循环拉伸（30%应变）过程中PWS薄膜的电阻变化。

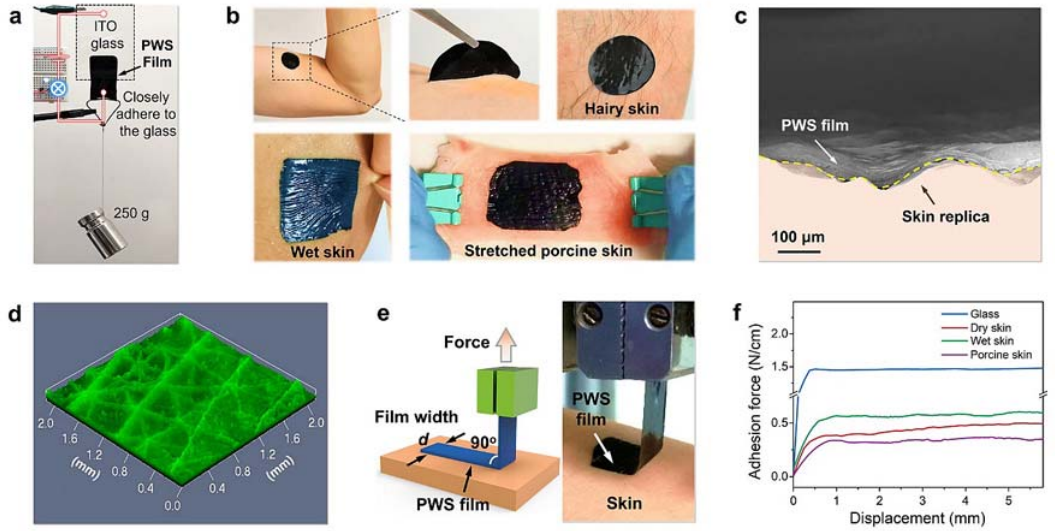

图3. PWS薄膜的粘附性能。a 承载250g重物的PWS薄膜牢固粘附在ITO玻璃，构成稳定的导电回路；b PWS薄膜牢固粘附在光滑、带毛发皮肤、湿润皮肤以及拉伸变形的皮肤表面；c PWS薄膜紧密贴合于皮肤复制物表面的微细纹路；d 将PWS薄膜按压贴敷于皮肤复制物表面，揭下的PWS薄膜可复制出皮肤纹路；e PWS薄膜在皮肤或基底表面的粘附力测试；f PWS薄膜在干、湿皮肤、玻璃及猪皮表面的粘附力。

与文献中的干电极和商业化的凝胶电极相比，PWS干电极具有较低的皮肤接触阻抗（82 KΩ cm^2@10 Hz）和优异的稳定性，在静态、动态检测过程中产生的信号噪音极低，可以实现在干、湿皮肤以及身体运动等复杂状况下高分辨检测心电、肌电以及脑电等信号。而且，可以作为新型人机界面交互式电子皮肤，PWS干电极可以准确记录肱桡肌和屈腕肌等部位的肌电信号，从而精确分辨单根手指，以及手部和手臂运动，并实现利用肌电信号实时远程控制机械手臂精确运动。

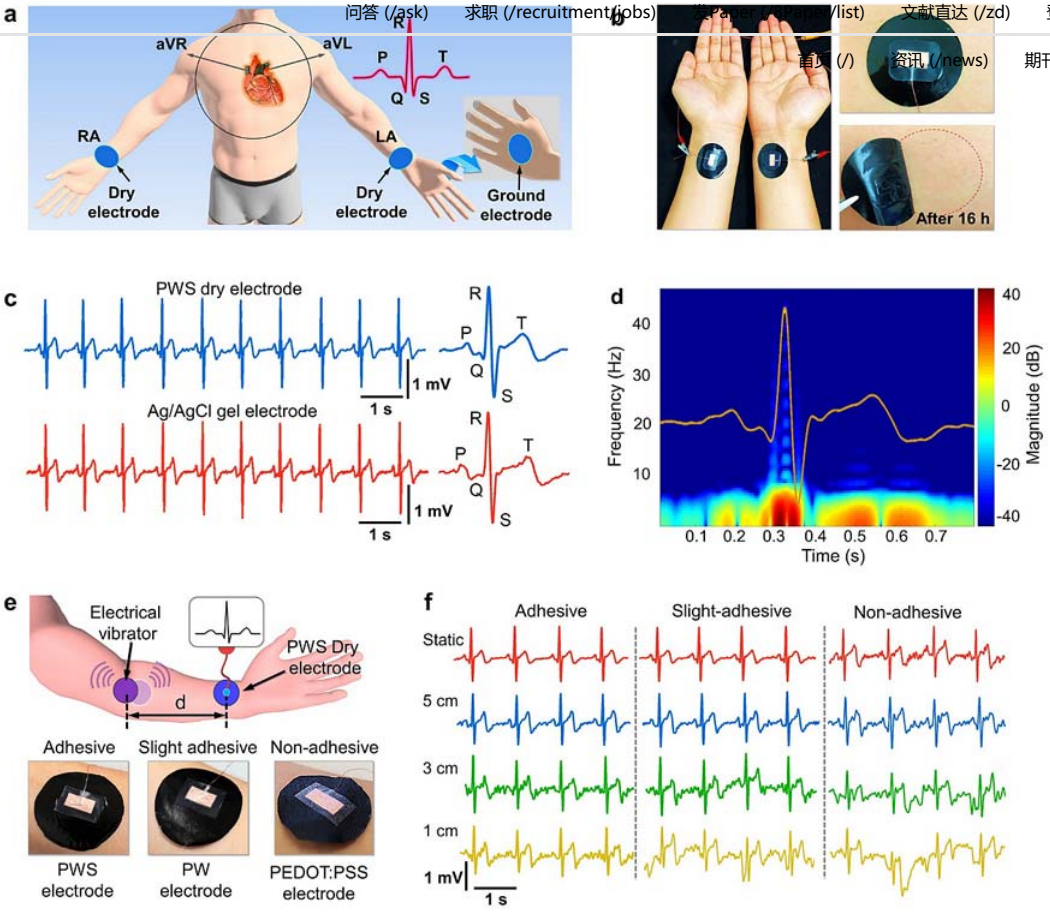

图4. PWS干电极检测心电信号性能。a, b PWS干电极检测心电的贴敷位置；c PWS干电极（蓝色）和商业化Ag/AgCl凝胶电极（红色）检测的心电信号；d PWS干电极检测的心电脉冲图谱（频率0-45Hz）；e，f粘附性PWS干电极、轻微粘附PW干电极和不粘的PEDOT薄膜电极在震动皮肤表面测试心电信号。

通过与新加坡国立医院的**Raymond Seet**教授的合作，他们还深入研究了PWS干电极在临床实践中的应用性能。针对患有心房纤维性颤动疾病的病人，PWS电极可以有效检测到病人的心律不齐及心电P波异常缺失等症状。另外，利用PWS干电极能够快速准确检测出病人肱二头肌持续性收缩，以及肱二头肌肌腱应激反应过程中的肌电信号，用于协助肌肉神经康复的诊断和治疗，表现出优异的临床应用性能。

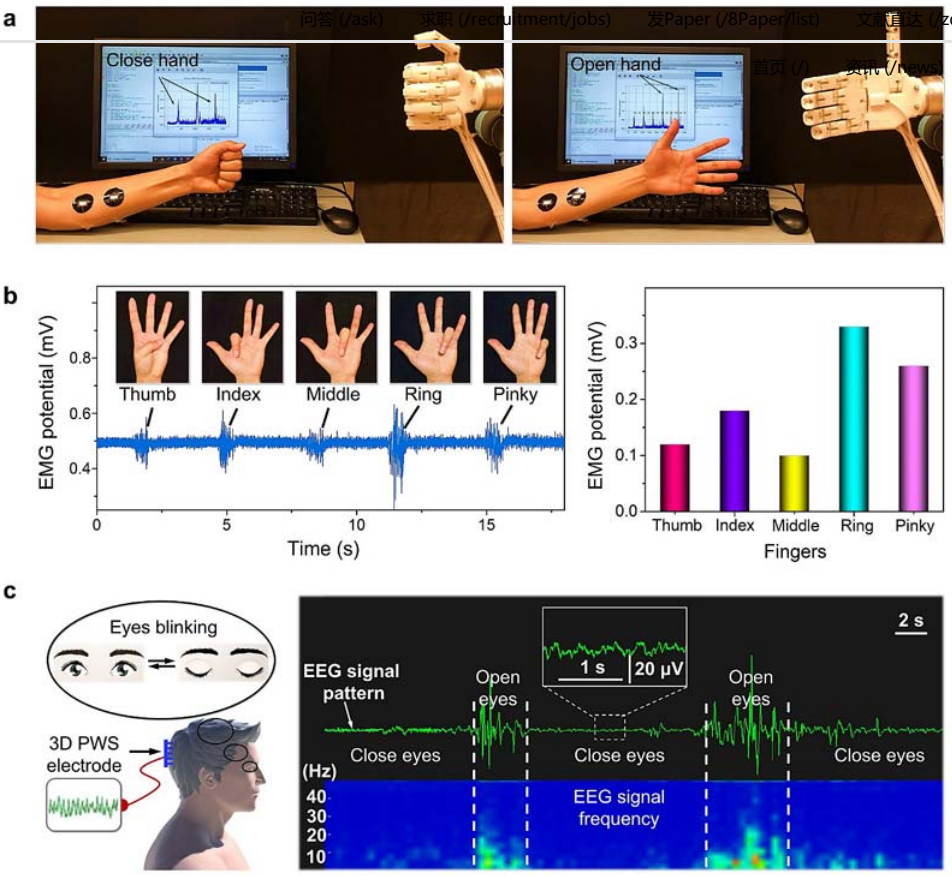

图5. PWS干电极检测肌电和脑电信号。a PWS干电极检测肌电信号并利用肌电远程控制机械手臂运动；b PWS干电极检测不同手指运动产生的肌电信号；c 三维结构PWS干电极穿过头发检测后脑头皮的脑电信号。

该成果发表在***Nature Communications*** 上。通讯作者是**欧阳建勇**教授和**任洪亮**教授，第一作者是**张磊**博士和**Kirthika Senthil Kumar**。

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